A STUDY OF THE WOUND-ON-TENSION MEASUREMENT METHOD IN CENTER WINDING CONDITION ON TYVEK® WEBS

BY

KARTHIK AYODHIRAMANUJAN

Bachelor of Engineering

South Gujarat University

Surat, India

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure	Page

Figure Page

LIST OF EQUATIONS

NOMENCLATURE

HDPE	High Density Poly Ethylene
WOT	Wound on tension
NIT	Nip Induced Tension
WHRC	Web Handling Research Center
Pli	Pounds per Liner Inch
E_r	Radial/Stack Modulus
E_t	Tangential Modulus
K1	Offset or Scale Factor
K2	Basic spring constant of the material
μ	Coefficient of friction
μ_{st}	Static coefficient of friction
N	Normal force
Tw	Web tension
U	Radial deformation of the outer layer of a wound roll
S	Nominal diameter of a wound roll

CHAPTER 1

INTRODUCTION

A web is a continuous, flexible strip of material such as paper, plastic film, metal foil, textiles and nonwoven materials, which are stored at least on an intermediate basis in wound rolls. The quality of the roll depends on the winding process and the types of winding differ in the method of application of torque. Much of the winding is currently accomplished via the center winding technique with an undriven nip roll. This technique requires that the winding torque be supplied to the center (core) of the winding shaft. In the surface winding process, the torque is applied to an impinging nip to turn the core. Many researchers have proved that the interlayer pressure in a center wound roll is higher than that of the surface wound rolls.

There are many methods to measure the internal pressures developed in a wound roll, few of them are destructive and interfering tests. Examples of such a test would be the Cameron gap test and the J-line test. These methods are used for research purposes only. The Wound on tension measurement is one of the methods of roll structure measurement that was developed by Pfeiffer. This method, though nondestructive is interfering as proved by Good et al.

The wound-on tension (WOT) measurement requires the outer most layer of the web to be pulled away from the winding roll and a measure of the web tension is made prior to returning the web to the surface of the winding roll. As the web is pulled away, there can be a frictional loss due to slippage, which results in lower WOT. Hartwig proved that the WOT measurement could be corrected to yield the true value of WOT had the web not been pulled away, for newsprint. The results show that the WOT appears to be directly a function of web tension and less a function of nip load in case of center winding. Newsprint is a high modulus web material (E = 600,000 psi).

The purpose of this research was to validate this method for other materials. The low modulus polymer material, High Density PolyEthylene was tested. The nip was covered with friction tapes and tested were conducted to study the effect of friction between the nip roller and the web on the WOT values.

There were some imperfections with old winder setup in the Web Handling Research Center that was primarily due to the dynamics of nip load. These dynamics instabilities were overcome by the new winder setup, results for which are provided. Finally, some conclusions have been made as to whether WOT behaves in accordance to the relations mentioned above for the HDPE material.

CHAPTER 2

LITERATURE REVIEW

The winding system can be divided into input parameters, process laws and output results or the roll quality. Several investigators have attempted to link input parameters to output results with various sorts of roll structure measurements.

Roll structure measurements using WOT is an active research area. Pfeiffer [1] was one of the forerunners in this field and has studied quantitatively the mechanics of the rolling nip on paper webs. He correlated the amount of nip-induced tension with nip force, drum diameter and paper properties. He concluded that the WOT increases irrespective of the web wound in center winding or surface winding process.

Pfeiffer [2, 3] investigated the effect of nip forces on wound-on-tension using an experimental winder as shown in figure 2.1. The web was threaded through the nip, taken around the load cell and taped to the core with some initial tension with nip force on. Pfeiffer noted an initial slope in the WOT Vs. nip force graph that represented an effective paper-to-paper friction coefficient region. He implied that the WOT cannot exceed the normal force exerted by the nip given by the equation,

$$\mathrm{WOT} \leq \mu_{st} N, \qquad \{2.1\}$$

where μ_{st} is the friction coefficient between the surface winding drum and the nip roll.

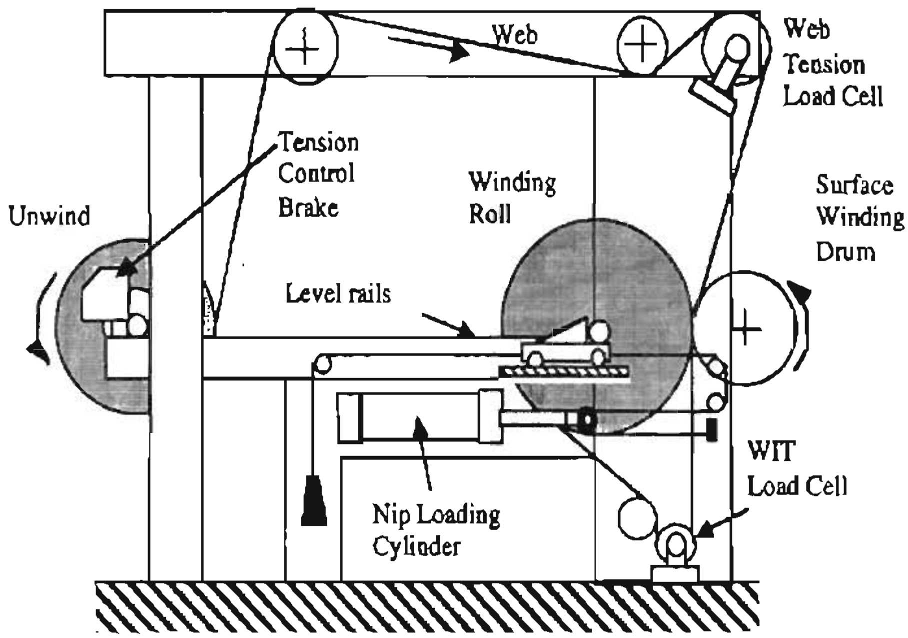

Figure 2.1. Pfeiffer's experimental setup

Pfeiffer conducted the experiments on surface winders and hence the limit given equation 2.1 is applicable to surface winding processes only. Another limit, which is smaller and applicable to both center winding and surface winding appeared in a paper authored by Good, Wu and Fikes [4] and in a TAPPI paper by Good and Fikes [5]. The limit is given by the equation

$$NIT \leq \mu_k * N, \tag{2.2}$$

where μ_k is the web/web kinetic friction factor.

Figure 2.2 shows that the WOT increases with nip force for different web tensions. The curve for Tw=0 implies that the WOT is in its minimum for any nip force and that the web cannot be wound with a negative tension.

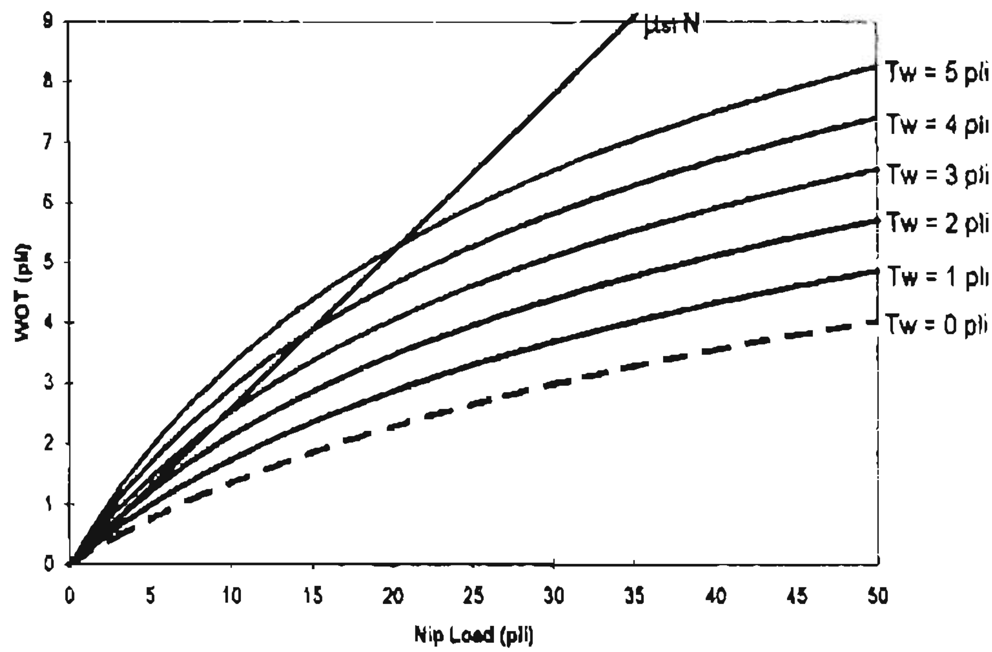

Figure 2.2. Pfeiffer's WOT curves

Rand and Eriksson [6] experimentally confirmed some of the theories using small strain gage transducers attached to the paper web. They showed that the web tension drops to a minimum before entering the nip and that the rolling nip elevates the wound-on-tension on the outgoing side of the nip to a level higher than either the minimum tension or the original web tension.

The study of roll quality measurements, nip induced tension mechanisms, finite element analysis, and air entrainment problems during winding, web wrinkling had been the subject of research at the WHRC. In 1992, Markum [7] published a study on nip mechanics of nip-induced tension. The tests were on paper and he established that the nip-induced tension (NIT) is a function of nip load and the co-efficient of friction .He found that the kinetic coefficient of friction has to be used instead of static coefficient in calculating the NIT. Using limited range of diameters for the nip rollers, he proved that the NIT was independent of the diameter of the nip in the case of center winding.

Ning Cai [8] studied the effects of the nip roll compliancy upon center winding and surface winding. His work proved that the NIT mechanics is the intrinsic property of winding with the nip roller and the compliance of the nip roller had no effects on the NIT and the wound roll stresses. He concluded that friction coefficient played an important role in determining wound-on-tension. His experimental setup is shown below in figure 2.3. His work on compliancy was later found to be limited by Kaya [9], who found that compliancy did affect WOT when the nip loads are high and the angle of wrap of the web about the nip roll was sufficient.

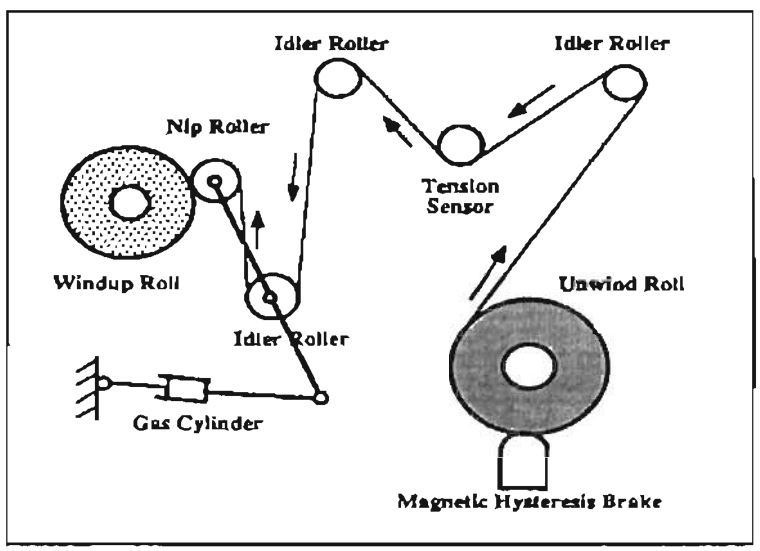

Figure 2.3. Ning Cai's experimental arrangement used at WHRC.

In the same year, Good, Pfeiffer, and Giachetto [10] were able to reason the difference in the experimental and theoretical tension values predicted by the wound roll models for center winding conditions with no nip roll. They found that the web tension was much less than that which was known to exist in the web prior to entering the winder. Their work corrected the total stress in the outside layer to be:

$$T = T_w + E_t * U / S \qquad \{2.3\}$$

Where U is the radial deformation of the outer layer is always negative, as the outer layer will always attempt to compress the roll body inward and S is the nominal diameter. Although this was important when center winding with a nip roll, tension loss has never been witnessed on center winders with nip rolls or surface winders.

In the recent years, Hartwig [11, 12] conducted a serious of experiments to study the wound on tension measurement method for the qualitative determination of the roll structure. There were several interesting conclusions from his experimental work.

1) He concluded that the WOT measurement is an interfering technique.
2) In some cases, he was able to correct the pull-tab data to yield the true value of WOT. He has thoroughly dealt with the description and usage of the pull-tab and various other pressure measurement techniques. His experimental conditions are summarized as follows:

Table 2.1 Hartwig's operating parameters for Newsprint.

Winding machine operating parameters in Hartwig's experiments	
Speed (feet/min)	300
Web Tension (lbs)	6
Nip Diameter (in)	4, 10
Wrap Angle	180^0

3) The WIT in center winding appeared to be a function of web tension and is less dependent on the nip load, in total contrast to surface winding for the case of 180^0 wrap angle. But Pfeiffer 's experiment [3] showed that at low wrap angles, the WOT is more dependent on the web tension.
4) The Nip induced tension was independent of the winding process. Hartwig found that center winders can exist better control over WOT when there is a high angle of wrap about the nip roll since the web tension can be varied to directly affect the WOT at any nip load. Thus rolls can be center wound at low nip load and high Wound-on tension resulting mainly from the web tension.

Balaji [13] performed similar experiments on a low modulus material, Tyvek®[1] at WHRC. Tyvek® is spun bond nonwoven material, made of PolyEthylene fibers. His work on surface winding process concluded that the WOT was a function of nip load and web tension. Both interlayer slippage and slippage between the web and the nip roller

[1] Tyvek® is a trademark or registered trademark of E.I. du pont de Nemours and Company or its affiliates.

caused a decreased WOT. At lower nip loads, the decrease in WOT was not due to the web/web kinetic coefficient of friction.

OBJECTIVE OF THE RESEARCH WORK

The objective of this research work is to study the WOT due to center winding for a web material whose properties are substantially different from newsprint. The quest is to determine if conclusions on WOT drawn from newsprint, a high modulus web that is reasonably homogenous, also apply to lower modulus material, which may be less homogenous. Tyvek® will be used in this study.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 WINDING MACHINE DESCRIPTION

The winding experiments at the Web Handling Research Center were initially performed using the winder setup given in figure 2.3 as used by Ning Cai [8]. The nip load was applied through an arm, with nip roller at one end, an idler at the center and an air cylinder at the other end. The dynamics of the system were unstable due to the fact that the nip load increased throughout the experiment and this fact had to be considered while calculating the roll structure and was tedious.

Hartwig [12] used a better nip application design for his experiments as shown in the figure 3.1. The nip roller carriage had facilities to vary the wrap angle of the web around the nip and also the diameter of the nip roller. The application of load and lateral motion of the nip were achieved through pneumatic cylinders. The nip load was measured with S-beam load cells that were in force feedback system with an e-p transducer. The WOT roller was mounted on a BLH load cell and the rollers preceding the WOT roller were placed such as to give the web an 180^0 wrap angle around the WOT roller. The data acquisition and control was taken care with the help of a National Instrument Data Acquisition card. A LabView program was used to control the nip load and record the values of WOT, speed, web tension and nip load throughout the experiment.

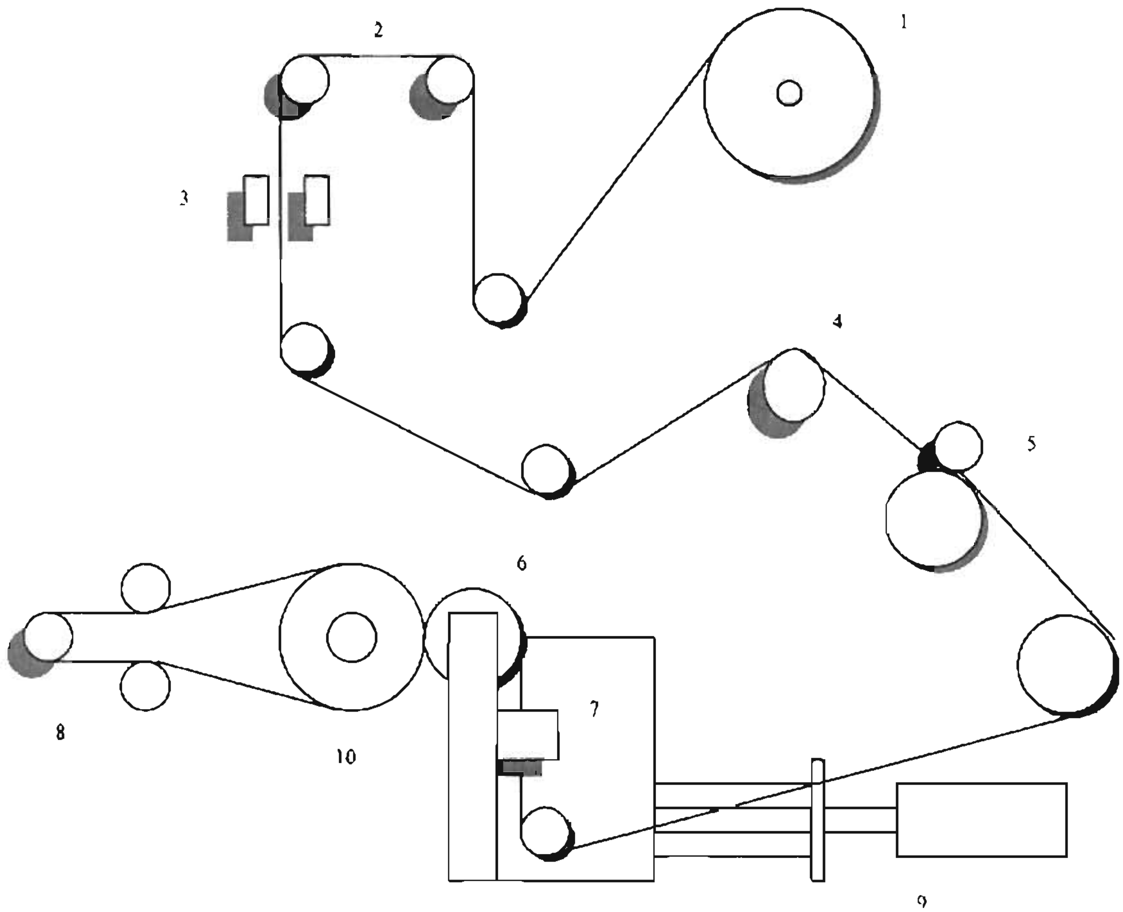

Figure 3.1 Experimental set up used by Hartwig

Legends:

1. Unwind station
2. Web lateral motion guide
3. Infrared guide
4. Load cell to measure web tension
5. Speed comparator
6. Nip roller
7. Load cell to measure nip load
8. Load cell to measure WOT
9. Pneumatic cylinder arrangement
10. Winding station
11. Idler to set the wrap angle.

In this setup, the web is unwound from the unwinding station, which is mounted on a magnetic hysteresis brake and is in a feedback loop with the web line tension load cell. The web is then passed through a FIFE model web guide and an infrared gate sensor controlled by a FIFE A-9 signal processor. The web is then passed through a series of rollers, including web line tension load cell and a web line speed servo tachometer. The tachometer is in feedback loop with a 5 HP Vector AC drive through a controller. The drive is connected to a Turner Uni-Drive 5 speed gearbox that allows for variable web speed. The web is rewound on an aluminum core mounted on the rewind shaft. Timing pulleys drive the rewind shaft. The winder has the facility to wind in both surface winding and center winding process and also with or without the web is being passed over the WOT rollers. The web, before fed to the core is passed over the nip roller at 180^0 wrap angle. The location of the idle roller just before the nip roller can be adjusted to set different wrap angles.

The difficulties posed by nip mechanics in Hartwig's setup forced a rethinking of nip load mechanism. He used a system by which nip load was applied using a single cylinder through a nip support, which hosted the entire nip mechanism along with the roller preceding the nip. When a nip load was applied during winding, the over hanging mass, measuring about 70 lbs, was subject to severe vibrations due to factors like unevenness of the wound roll and the fluctuating pressure inside the air cylinder applying the nip load. The fluctuation in nip load was very high and produced a significant error band at almost all the nip loads. This forced a new design of the nip mechanism; if the experiments were to be conducted a very low or high nip loads.

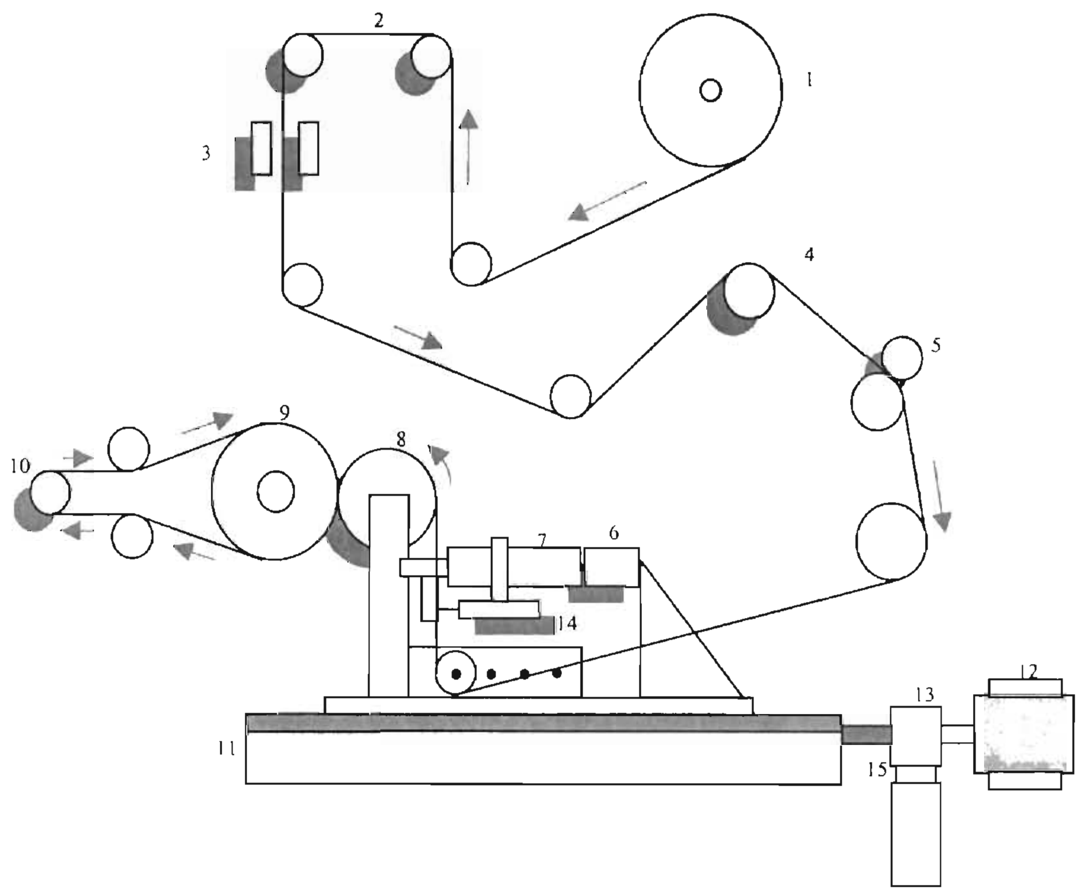

Figure 3.2 New winder setup at WHRC

Legends:

1. Unwind station
2. Web lateral motion guide
3. Infrared sensor for the lateral guide
4. Load cell to measure web tension
5. Speed comparator
6. Load cell to measure nip load
7. Air cylinder to apply nip load
8. Nip roller
9. Rewind station
10. Load cell to measure WOT
11. Linear guides
12. AC motor
13. Speed reducer
14. LVDT
15. Ball screw

In the new design, the over hanging mass of the nip mechanism was replaced by a carriage moving on linear rails guided by a ball screw. A Reliance Electric AC motor with Dayton speed reducer powered the ball screw. The carriage comprised of the nip roller, nip arm, an idle roller, air cylinders to apply nip load, a LVDT and load cells. The air cylinders were connected to the nip arm at one end and to the load cells at the other end. A LVDT was attached to the piston of one of the air cylinders. The LVDT is in a feed back loop with the AC motor. Depending on the direction of motion of the piston, the carriage moves forward or backward.

The advantages of the new system over the older setup are:

1) There was a minimal loss in the system. Hence, most of the cylinder force was transmitted to the nip.
2) The overhang mass was eliminated. This resulted in a lesser fluctuation of the nip load than the previous setup. This was evident even when the roll was uneven.
3) By changing the capacities of the cylinders, we can achieve the necessary change in the range of nip loads.

A comparison of the nip loading of both the setup is given in figures 3.3 & 3.4.

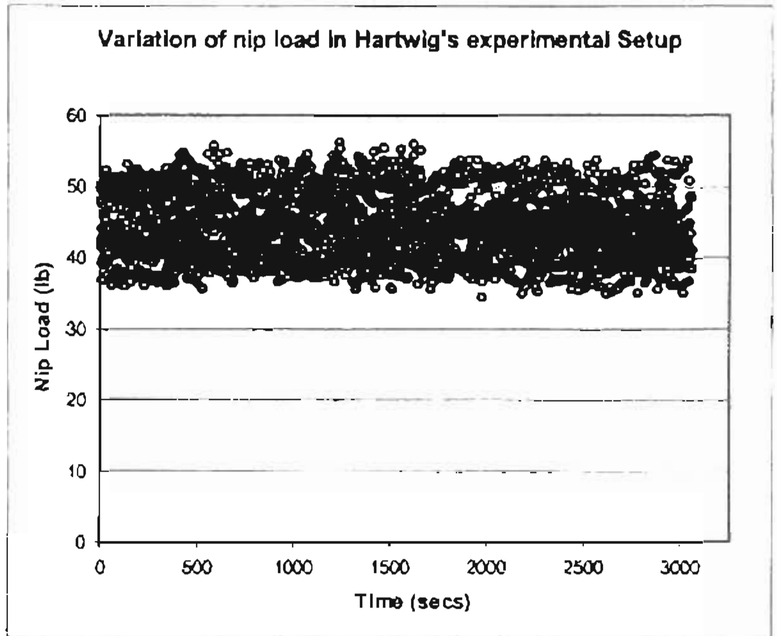

Figure 3.3 Nip load variation in Hartwig's experimental setup

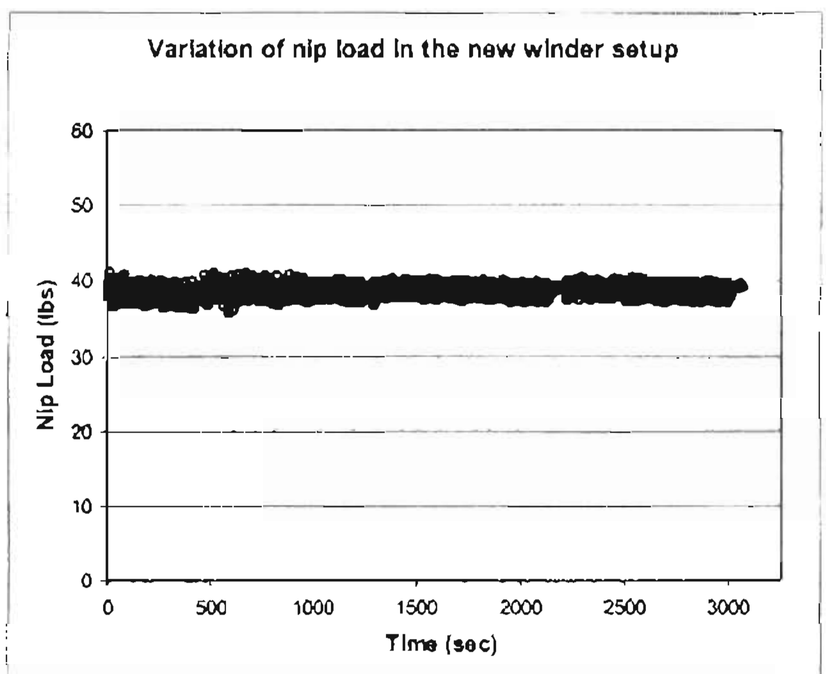

Figure 3.4 Nip load variation in the new winder experimental setup

The web line tension was controlled using a DIGITRAC tension controller made by Magpower Power Systems, Inc. By adjusting the stability factors, just after the start of the winding experiment, the fluctuation in web line tension can be limited to within 5% of the desired value.

The operating conditions were obtained after winding few rolls at different nip loads, web tensions and speeds. The final operating parameter range is given in table 3.1 and table 3.4.

Table 3.1 Experimental operating conditions

Winder operating parameters	
Winding speed	100 ft/min
Nip Diameter	6 in
Web width	6 in

Table 3.2 Operability range for different winding tensions and nip loads

Web tension (pli)	Nip load (pli)					
0.5	4	8	16	24	32	40
1.0	4	8	16	24	32	40
1.5	4	8	16	24	32	40

While considering the experimental tests, the surface winding constraints were also considered. In surface winding, experiments at a web tension of 1 pli and a nip load of 4 pli were not possible because of slippage of web roller over nip roller and interlayer slippage as explained by Balaji [13]. But this condition was not seen in center winding, hence was also included in the experiments.

3.2 MATERIAL TESTING

The knowledge about the material properties is essential for the study of winding processes. The properties that were measured are, the radial modulus, in-plane modulus and friction coefficients.

3.2.1 Radial modulus (E_r):

The radial modulus (E_r) is an input parameter for mathematical models like Hakiel's [15] to predict the pressure distribution in a wound roll. A 6 x 6 x 2 in^3 stack of HDPE web was used for testing the radial modulus on an Instron Pressure testing machine. The machine had platens of square cross sections. A LabView program was used for data acquisition and control. The machine was programmed to apply the load from 0 to 200 psi pressure and record the pressure verses strain data. The pressure-strain characteristic is non-linear in nature for the HDPE web.

There are different methods of obtaining the radial modulus from the above data. One of the methods is to differentiate the best curve fit for pressure versus strain data and then curve fitting the line obtained using the equation values against pressure data. Another method is the difference method of differentiation. Advanced mathematical softwares could be employed to directly differentiate the pressure-strain data to obtain the radial modulus curve. For this study, a radial modulus function in terms of pressure was obtained using Microsoft Excel program. The LINEST macro was used to estimate the differentiated values and these values are plotted against the pressure data. A polynomial curve fit of third degree was obtained.

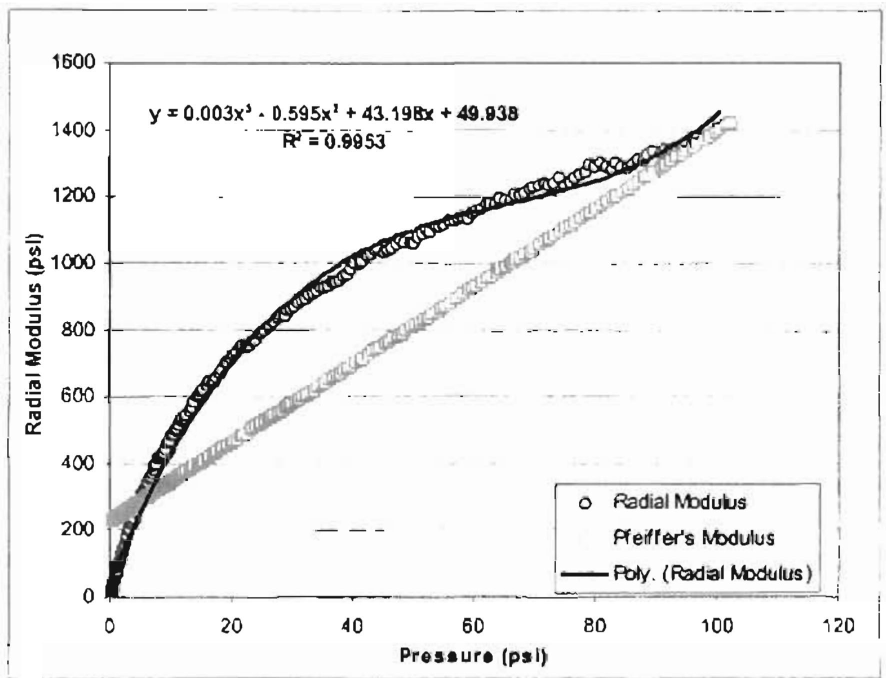

Figure 3.5 Radial Modulus plot, curve fit from Pressure vs. Strain data

The Pfeiffer's [10] expressions are given below.

$$P = K1\ (e^{K2\varepsilon} - 1) \qquad \{3.1\}$$

$$E_r = dP / d\varepsilon = K1\ K2\ e^{K2\varepsilon} \qquad \{3.2\}$$

$$E_r = K2\ (K1 + P) \qquad \{3.3\}$$

The coefficients in the above equations K1, K2 were determined by the solver package in the Microsoft Excel Program. The error between the experimental data and the data computed using the Pfeiffer's equation was minimized to obtain the following values for K1 and K2.

Table 3.3 Coefficients K1 and K2 in Pfeiffer's equation

Coefficients of Pfeiffer's equation	
K1	19.7
K2	11.6

3.2.2 In-plane modulus (E_t):

The in-plane modulus (E_t) of the material is about 75000 psi as quoted by Tyvek. But the experiments at the WHRC established the value to be about 59000 psi. To establish the value, a 50 ft of HDPE web was used. One end of the web was tapped and other end was connected to a force gauge. An index was marked at the end that is connected to the force gauge. The web was pulled slowly. The displacement was recorded for predetermined values of the force. Three such tests were performed and the average values were used to obtain the value of in-plane modulus. The in-plane modulus test curve was shown in figure 3.6 below.

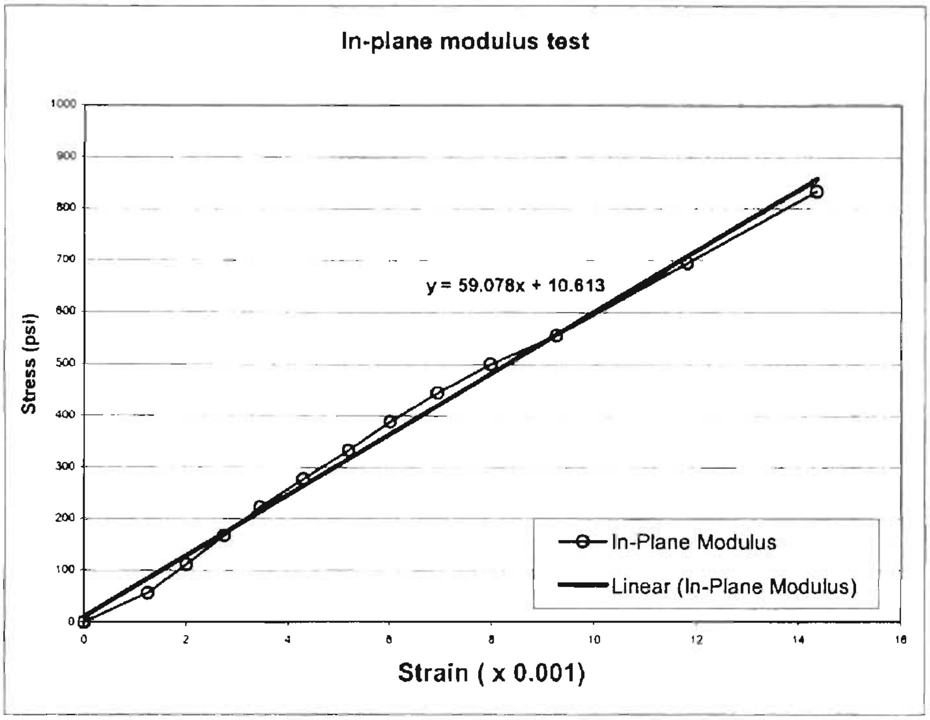

Figure 3.6 In-plane modulus calculation curve

3.2.3 Pressure measurement:

In this study, pull-tabs were employed to measure the pressure in the radial direction. These were calibrated before each set of experiments. The pull-tabs are made of 0.001 in thick stainless steel feeler gauges made by Precision Brand Products Inc. To increase the uniformity of friction, the pull-tab was encased in a brass sheet made by the above company. The brass casing along with the pull-tab was kept in the middle of a 2 in thick HDPE web stack for calibration on an Instron pressure testing machine. A Force gauge was used to pull the pull-tab after applying a known value of load.

A curve is plotted for the known pressure vs. pull force value. This curve is used to interpret the radial pressure value in the wound roll during the experiment. The pull-tabs are pulled thrice and their average values are used in calibration. Typically, the curve is linear as shown. The pull-tabs are inserted into the wound roll in a direction perpendicular to the motion of the web. Once the roll is wound completely, the pull-tabs are pulled thrice as during calibration. Their average value is used in computing the radial pressure.

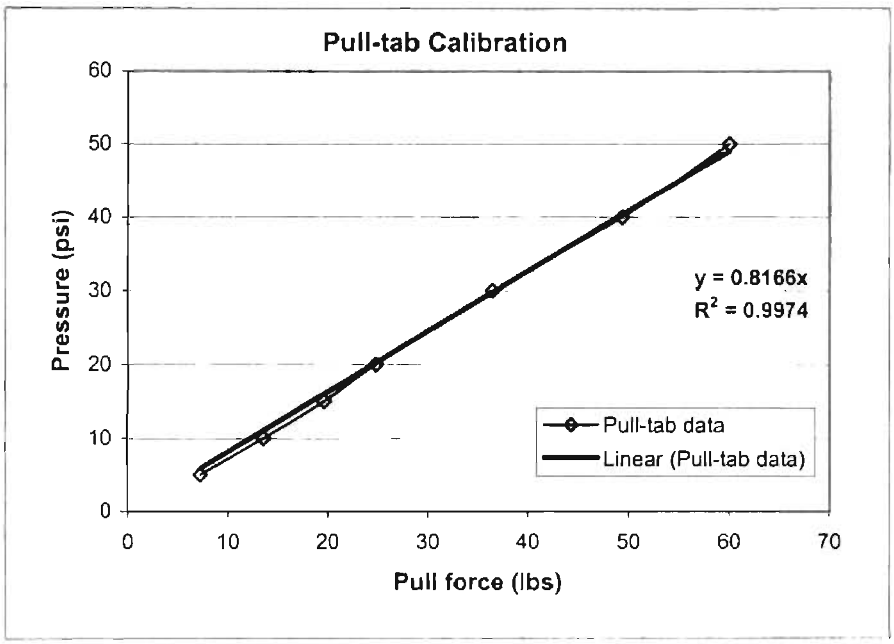

Figure 3.7 A typical calibration curve for a pull-tab.

Hartwig, in his thesis had dealt in detail with various other methods of roll structure measurement like Cameron gap test [16], rhometer [17], Smith Roll Tightness Tester [18], Force Sensing Resistors [5], etc.

3.2.4 Friction tests:

In this study, friction tests were performed to determine the coefficient of friction between web to web and web to aluminum. A known weight of 11.65 lbs was used to measure the friction factors. The weight was fixed to one end of a piece of HDPE web. The web was passed over a 6 in aluminum core clamped at both the ends. A force gauge was used to pull the web and determine the frictional force. Three tests were performed and their average was used in determining coefficient of friction between web and aluminum. The kinetic coefficient of friction was then obtained using

$$T1 / T2 = e^{\mu_k \theta}, \qquad \{3.4\}$$

Where μ_k is the kinetic coefficient of friction and $\theta = \pi$ rads.

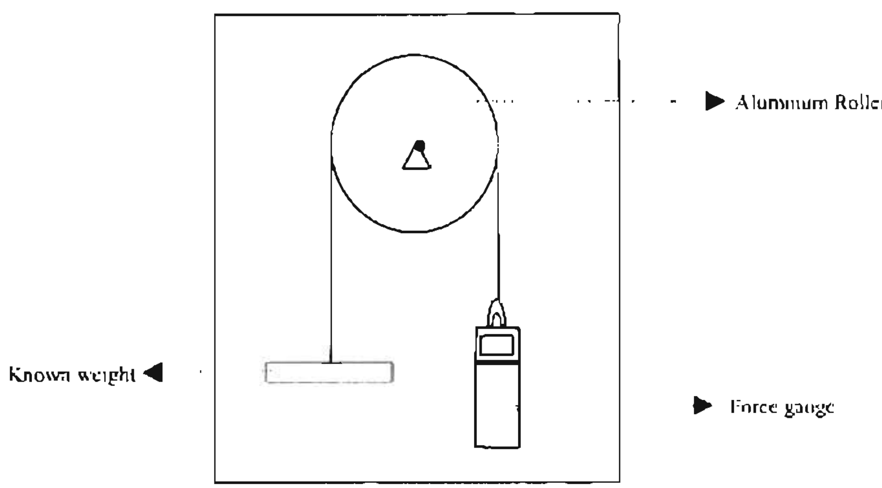

Figure 3.8 Friction measurement test

Similar tests were performed to determine the coefficient of friction between web layers. For this study, the aluminum core was first wrapped with a piece of HDPE material and the coefficient of friction was measured. The results are summarized in the table given below.

Table 3.4. Coefficient of friction factors

Coefficient of friction (μ)	
$\mu_{Aluminum-HDPE}$	0.138
$\mu_{HDPE - HDPE}$	0.202

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

Hartwig had established Wound-On-Tension measurement as a method to quantify roll structure. He investigated the WOT measurements on newsprint by two different methods; directly observing the WOT values from the WOT load cell and inferring the WOT from the pull-tab measurements. He established that the WOT measurement is an interfering method. The behavior of low modulus material like Tyvek® on WOT measurement is the topic of interest in this study.

4.1 BEHAVIOR OF WOT

For any material, the knowledge about the behavior of WOT by direct observation is useful before starting to experiment with WOT measurements using pull-tab. This knowledge will help us in determining the operating range for the experiments. The range was determined by winding the Tyvek® material for a set of web tensions and nip loads. When determining the set of experiments, the WOT behavior for surface winding was considered, so that the results could be compared. For surface winding the stick zone was at around a nip value greater than 40 pli.

To perform the initial test, the web was pulled away from the winding roll and passed over a WOT roller and fed back to the winding roll. The load cell attached to the WOT roller measure the WOT directly. A LabView program acquired WOT, nip load, web tension and speed dataset over the entire duration of the experiment. From the figure below, it can be seen that the WOT decreases with both web tension and nip load. After these initial tests, the set of experiments to make pull-tab measurements were determined to be 4, 8, 16, 24, 32, 40 pli nip loads at 0.5, 1.0, 1.5 pli of web tension, totaling 18 sets of experiments.

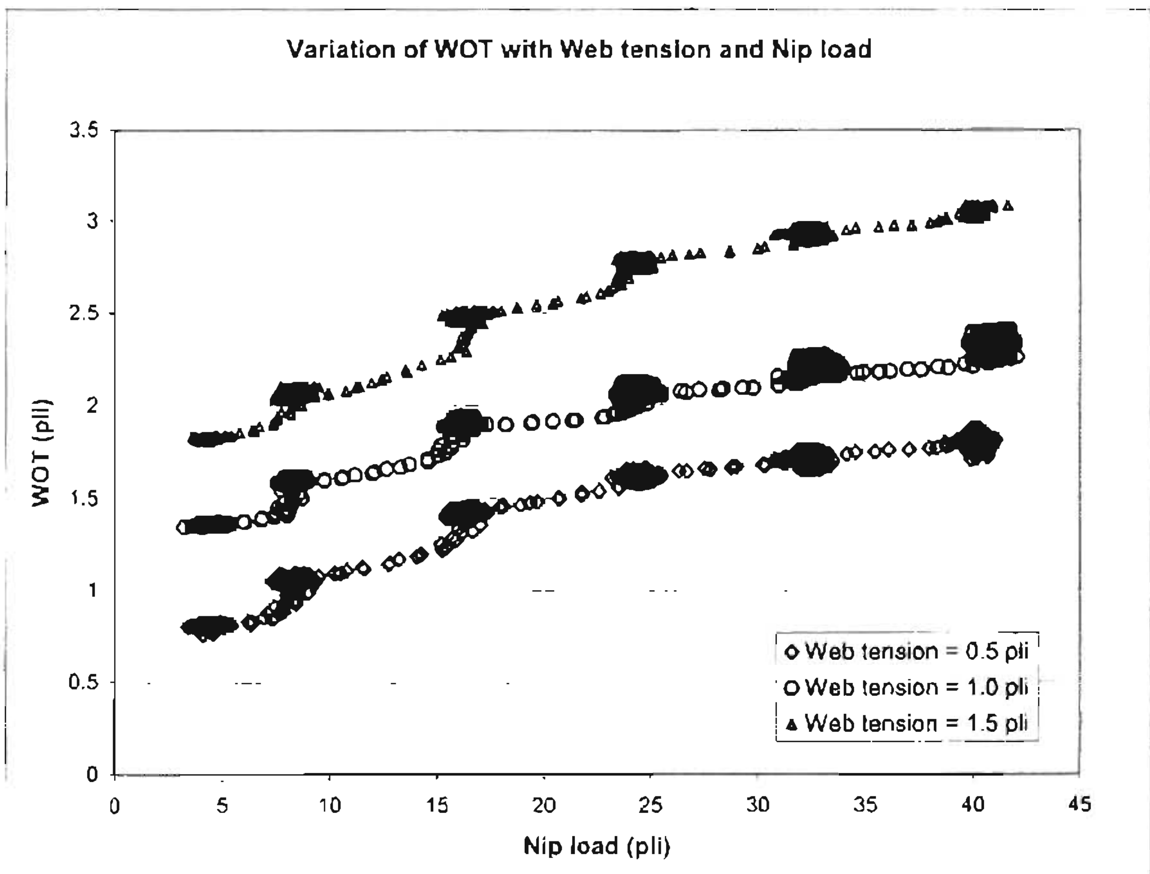

Figure 4.1 Behavior of WOT with web tension and nip load

4.2 EXPERIMENTAL PROCEDURE TO MEASURE RADIAL PRESSURE

WOT is measured indirectly from the measurement of radial pressure inside the wound roll. To measure the radial pressure, pull-tabs were inserted at certain radial locations and pulled with help of force gauges; the force being an indicative of the radial pressure at that location. The WOT rollers were not used in the study because Hartwig had established it to be an interfering method and the WOT observed would be less than the values inferred from the pull-tabs.

Before the start of the experiment, new pull-tabs were calibrated. The pull-tabs are inserted at 5 radial locations starting at around 0.6 in from the core. Typically, the wound roll is of 6.3 inches in diameter. Each experiment is repeated 3 times resulting in 3 radial pressure measurements at each location. The values are averaged and 95% confidence levels are established and plotted as error bars in the radial pressure verses radius plots. Table 4.1 shows a typical pull-tab reading.

Table 4.1 A pull-tab reading obtained on Instron pressure testing machine.

Pull Tab A					
Pressure (psi)	Load (lbs)	Trial 1 (lbs)	Trial 2 (lbs)	Trial 3 (lbs)	Average (lbs)
5	180	7.4	7.3	7.5	7.4
10	360	14	13.9	13.7	13.9
15	540	20.6	20.1	20.3	20.3
20	720	26.8	27.2	27	27.0
30	1080	40.4	40.3	40.9	40.5
40	1440	53.9	54.1	53.8	53.9
50	1800	67	66.8	66.5	66.8

Figure 4.2, 4.3, and 4.4 show the radial pressure curves for web tensions 0.5, 1.0 and 1.5 pli at different nip loads.

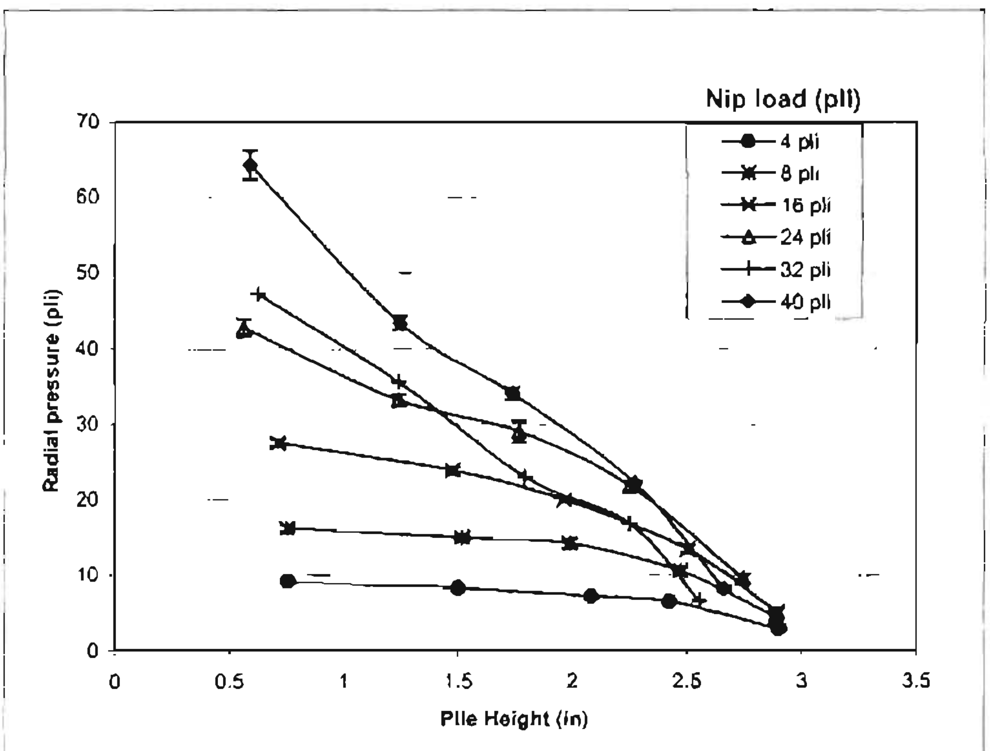

Figure 4.2 Radial pressure plot at constant web tension of 0.5 pli

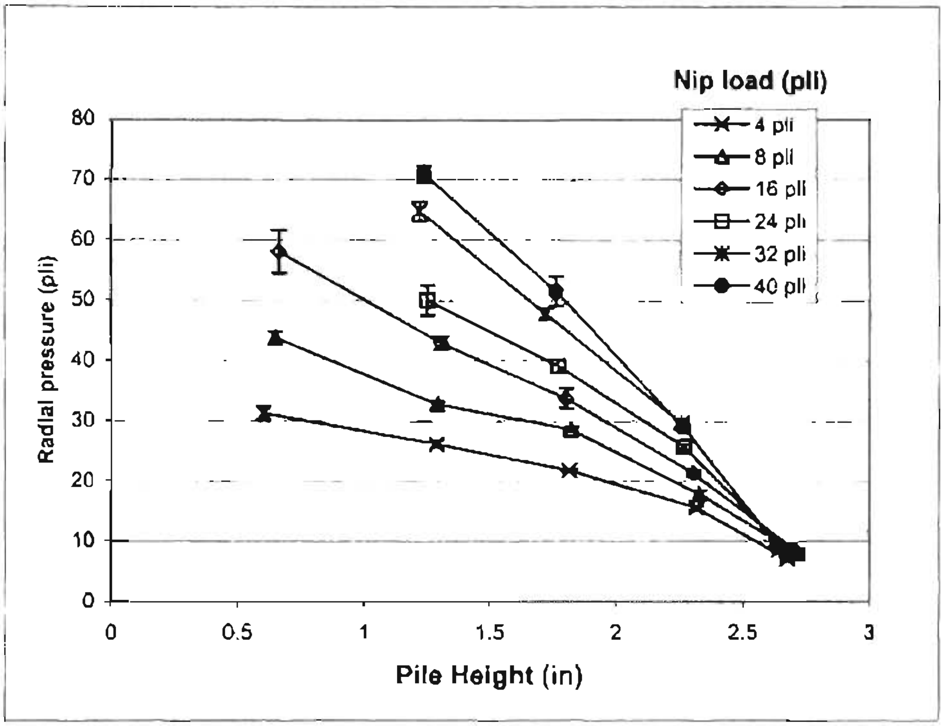

Figure 4.3 Radial pressure plot at a constant web tension of 1.0 pli

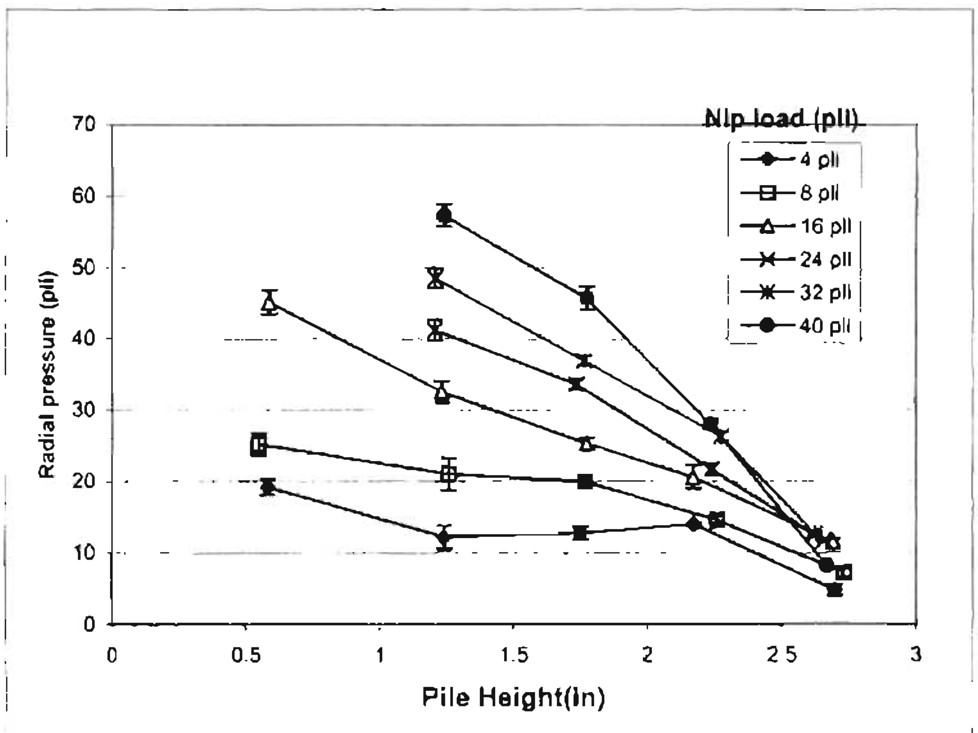

Figure 4.4 Radial pressure plot at constant web tension of 1.5 pli

4.3 AN ITERATIVE PROCEDURE FOR CALCULATING WOT

Hartwig used an iterative procedure to determine the WOT from pull-tab measurements using Hakiel's wound roll model. In this study, Winder 6.0 program was used to determine WOT from a known radial pressure profile calculated from the pull-tab measurements. The model requires few winding parameters as input, which are summed up below:

Table 4.2 Initial parameters to the Winder 6.0 software

Input to the winder 6.0 software	
Core outer radius	6.615 in
Wound roll outer diameter	12.415 – 12.815 in
Pfeiffer's constant K1	19.7 psi
K2	11.6
In-plane modulus (E_t)	59000 psi
Core Modulus	10E6 psi

The winder software does not have options to calculate WOT tension directly for a particular radial pressure profile obtained from the pull-tab measurement. But an iterative procedure has been adopted to determine the WOT. The radial pressure from the pull-tab measurement is plotted on the same graph as that of the model predicts. An error term is computed by summing the absolute errors between the winder computed radial pressure and pull-tab measured value at the recorded radial location.

Now, the program is run with a trial input to the winding tension value. The error is noted. Then the program is rerun with a new winding tension till the error term is a minimum. The winding tension corresponding to the minimum error term is the WOT. To use such an iterative procedure, the WOT should be a constant for any radius of the wound material for a particular winding conditions. Below is a figure of a direct WOT experiment run at web tension of 1 pli and a nip load of 6 pli of HDPE web material after achieving steady state winding conditions. The WOT is constant through the experiment. Hence, the iterative procedure is valid.

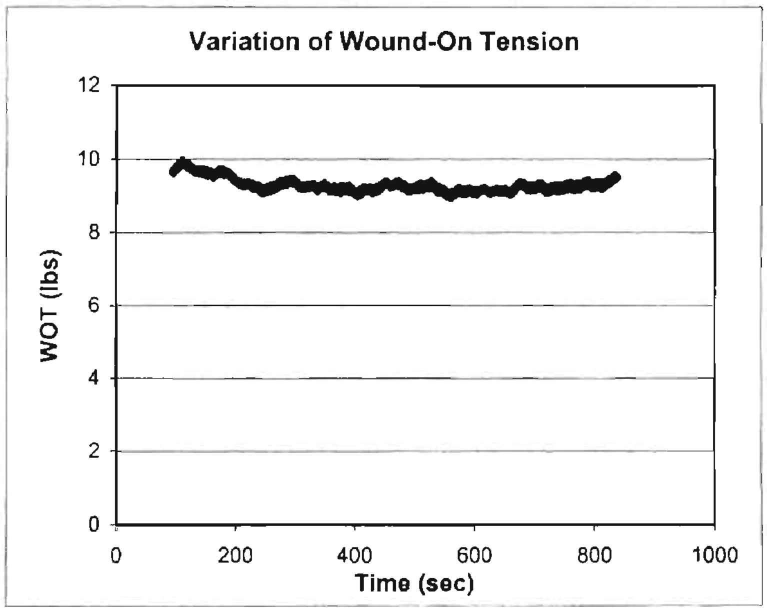

Figure 4.5 Behavior of WOT at web tension = 1 pli and nip load = 6 pli

It has been proved by Hartwig that the direct measurement of WOT is an interfering method and that there is a difference in the experimental and calculated values. A flow chart describing the iterative procedure is given in figure 4.6.

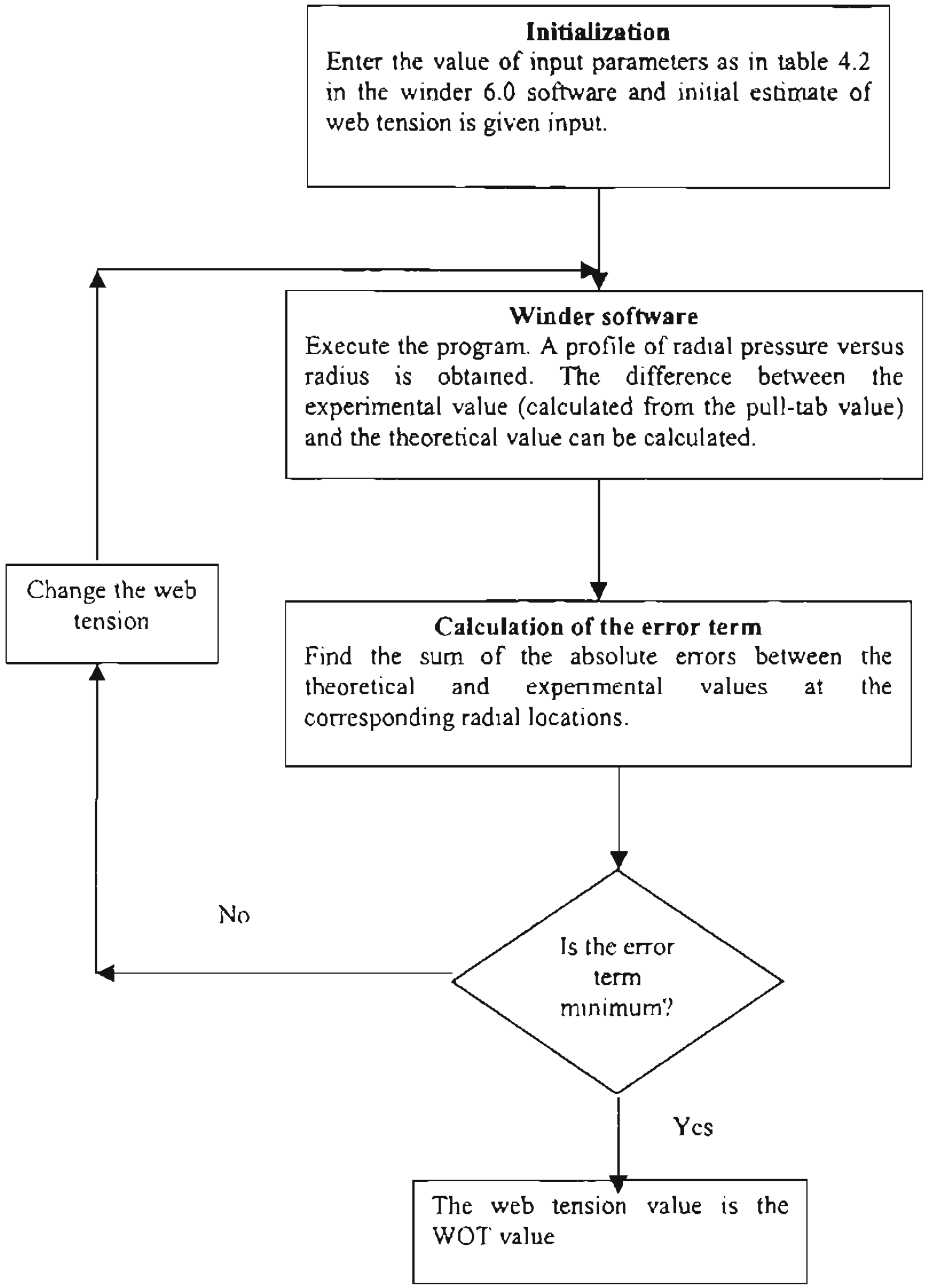

Figure 4.6 Flow chart for iterative procedure to calculate WOT

In this study, WOT values for all the experiment sets are computed using the above iterative procedure. A radial pressure plot of the experimental and theoretical value with a minimum error is given in figure 4.7.

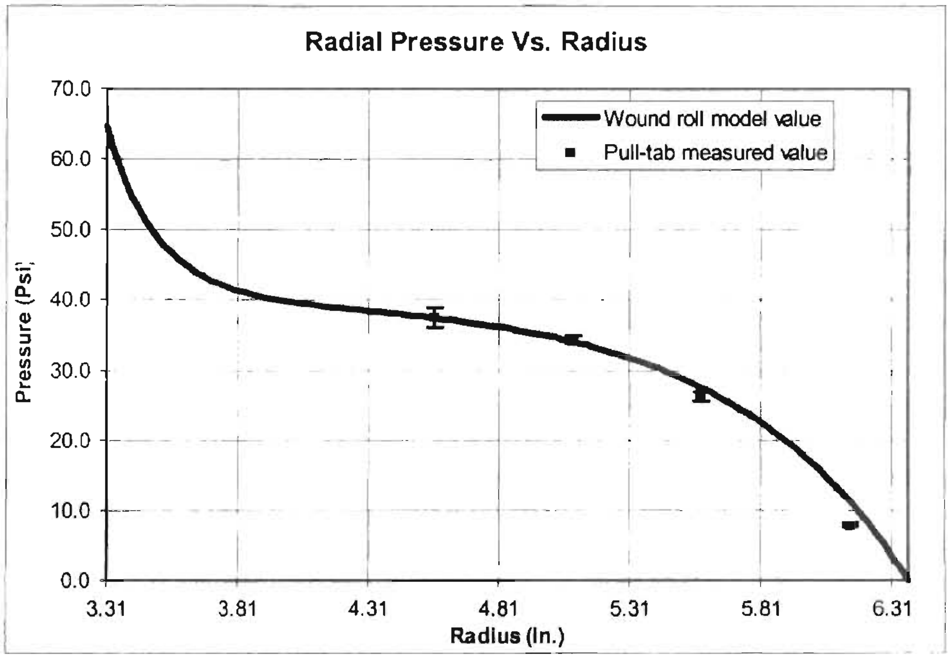

Figure 4.7 Radial pressure profile for web tension = 1 pli and nip load = 24 pli

In the above figure, a WOT tension value of 2.33 was calculated for a web tension of 1 pli and a nip load of 24 pli using the Winder software with minimum error between the theoretical and experimental values. A list of figures showing the radial pressure profiles obtained using winder code (Hakiel's model) is given in Appendix A. The calculated values of the WOT for all values of web tension and nip load is given in figure 4.9.

4.4 NIP INDUCED TENSION

It is known that the nip roller induces a component of the WOT above and beyond the web tension, the nip-induced tension. The source of this nip-induced tension is the elongation machine direction strain in the outer layer due to contact mechanics. As the incoming web, leaves the contact zone between the nip and the winding roll, the web tension undergoes an increase in tension, the nip-induced tension.

A sizeable loss of WOT is experienced as explained by Hartwig when direct WOT measurements are made. The decreased WOT which is measured is associated with friction loss and can be predicted using the capstan expression given below.

$$\text{WOT measured} = \text{WOT} / e^{\mu}{}_{w/w} . \theta, \qquad \{4.1\}$$

where $\mu_{w/w}$ is the kinetic coefficient of friction between webs and θ is the angle of wrap between the nip and the point at which the web is extracted to make the WOT measurements.

A comparison of WOT values measured directly against in the WOT values inferred from the pull-tab measurements is given in figure 4.8. Note that at lower nip loads, the ratio of the WOT (inferred) and WOT (direct) is about one. Hence there is no slip at lower nip loads for center winding cases using Tyvek®. It appears that the direct WOT measurements may not be interfering at lower nip loads.

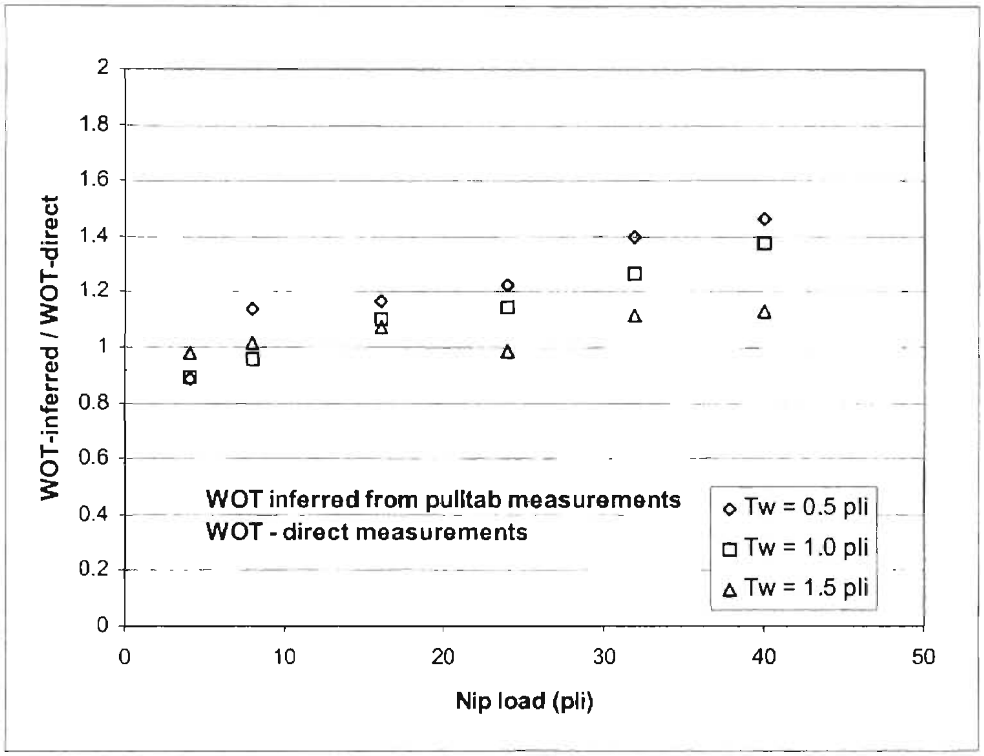

Figure 4.8 Comparison of directly measured and pull-tab inferred WOT values

The loss in WOT due to the slippage between the outer layer and the layer beneath, can be corrected to the original values as explained by Hartwig [12]. The web tension associated with each center winding case was subtracted from the measured WOT values and the results are plotted in figure 4.9 along with the measured WOT values. The NIT falls into a reasonable single curve for all the cases.

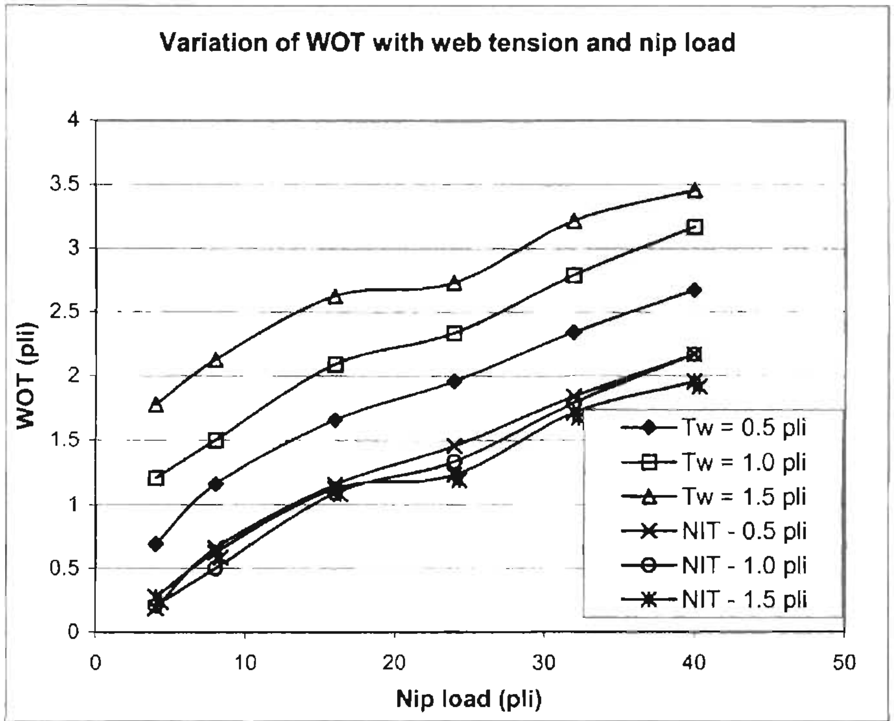

Figure 4.9 Variation of WOT-inferred with nip load and web tension

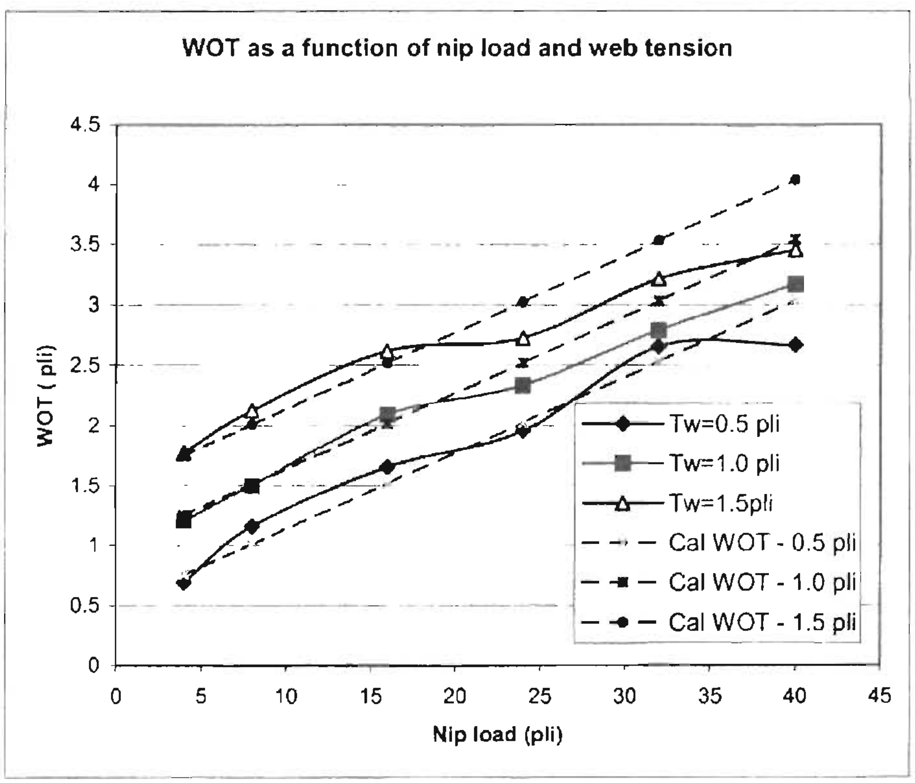

Figure 4.10 WOT values computed using the relation in equation 4.2

The slope of the WOT values in figure 4.10 is calculated using the equation

$$WOT = T_w + (\mu_{w/w} - \mu_{A/W}).\ N, \qquad \{4.2\}$$

where N is the nip load, T_w is the web tension, $\mu_{w/w}$ is the coefficient of friction between web layers and $\mu_{A/W}$ is the coefficient of friction between web and aluminum.

The results established by Good for newsprint material were based on the assumption of uniform friction between the web layers. But the slope of the WOT in figure 4.10 suggests the value that is a difference between the friction between web layers and the friction between web layer and aluminum.

To corroborate that the equation 4.2 is an appropriate expression for WOT for center winding, a set of experiments were carried out with the nip roller covered with friction tapes. Friction tapes are capable of increasing the coefficient of friction between aluminum and the web layer to a very high value. Friction tests were conducted in the manner explained in section 3.2.4. The kinetic coefficient of friction was measured to be 1.5 with a wrap angle of 180^0. Figure 4.11 shows the newer WOT values against the earlier measured values as in figure 4.1.

There was not much difference between the WOT values measured with the nip roller covered with friction tape and without the friction tape. But they were lesser than the WOT values inferred from the pull tab data using the iterative procedure.

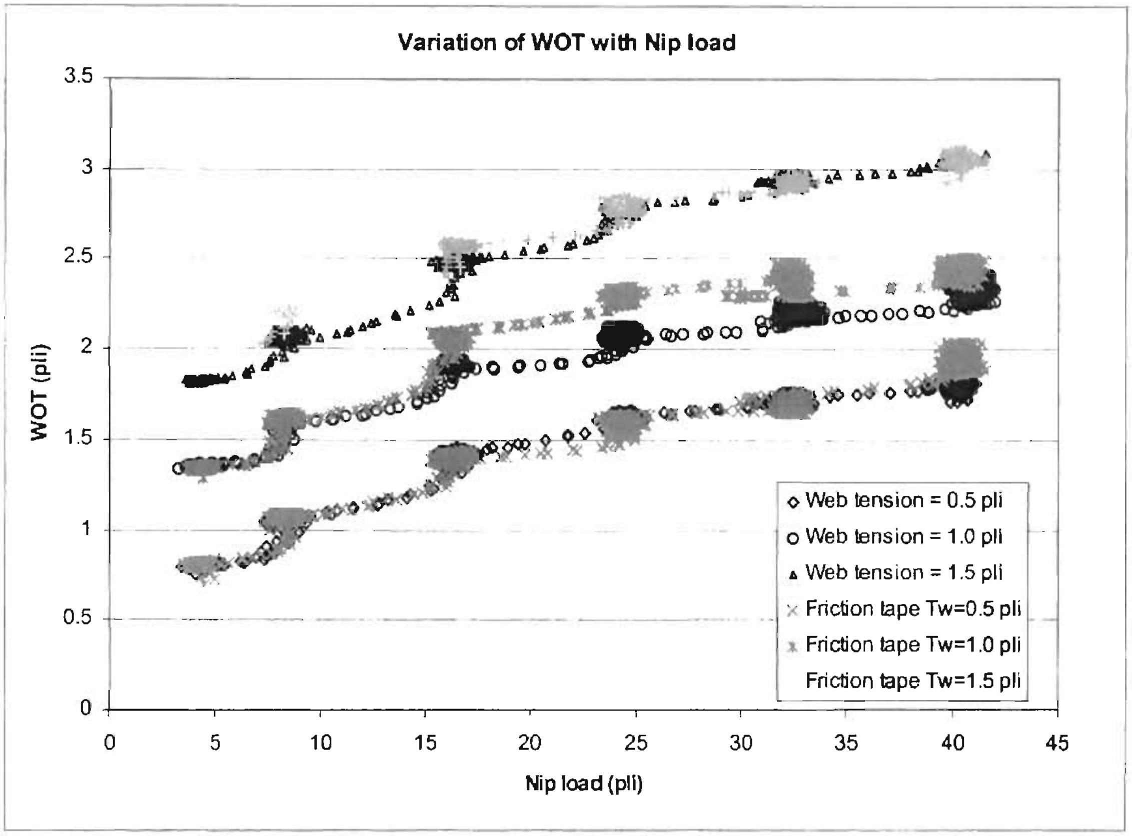

Figure 4.11 Comparison of WOT values for different nip roller surfaces

The equation 4.2 though valid for Tyvek web material may not be valid for all the cases. Though this may be offered as a solution to the winding conditions discussed above, it is unwarranted that the same relation holds good for all the winding conditions. All the above results are drawn, assuming the Radial modulus of elasticity to take the Pfeiffer's form. In the Appendix C, the above results are drawn with the polynomial form for Radial modulus (as given in figure 3.5) and compared.

CHAPTER 5

CONCLUSIONS

The following conclusions are drawn from the experiments carried out to evaluate the roll structure using WOT measurement for Tyvek® webs.

1) At lower nip loads, the Wound-On Tension measurement method appears to be a non-interfering method. (Refer Figure 4.8)
2) At higher nip loads, this technique yields a lesser value than the WOT values inferred from the pull-tabs as observed with newsprint.(Refer Figure 4.8)
3) The Nip-Induced tension appears to be a function of nip load only, as was observed with newsprint, a high modulus material. (Refer Figure 4.9)
4) The Nip-Induced tension depends, more on the difference between the coefficient of friction factors between web/web and aluminum/web. The equation 4.2 may be offered as a one-time solution for Tyvek® webs.

FUTURE WORK

The Wound-On tension measurement method is a proven method to study the roll structure of a wound roll. Its been studied for materials whose properties do not vary. But Tyvek® is a non-homogenous material. Its material properties can be better classified. There are variations in material density across the width. Hence it is necessary to study the micro properties of Tyvek® instead of macro properties. For example, the In-plane modulus test can be conducted at various sample lengths.

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APPENDIX A

PLOTS OF RADIAL PRESSURES FOR DIFFERENT WEB LINE TENSIONS AND NIP LOADS USING PFIEFFER'S FORM OF RADIAL MODULUS OF ELASTICITY

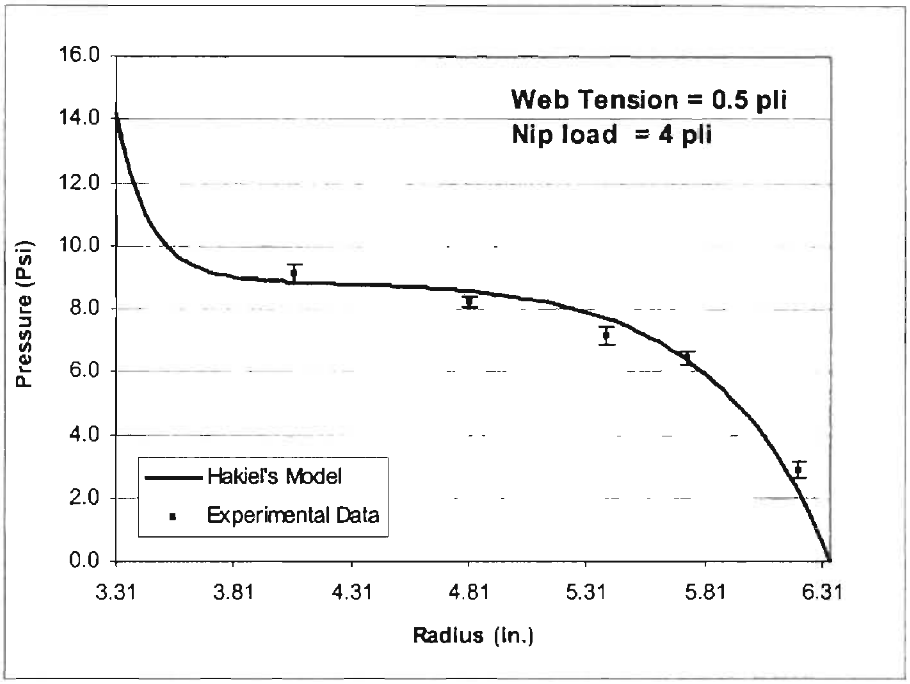

Figure A.1 Radial pressure profile at web tension = 0.5 pli and nip load = 4 pli

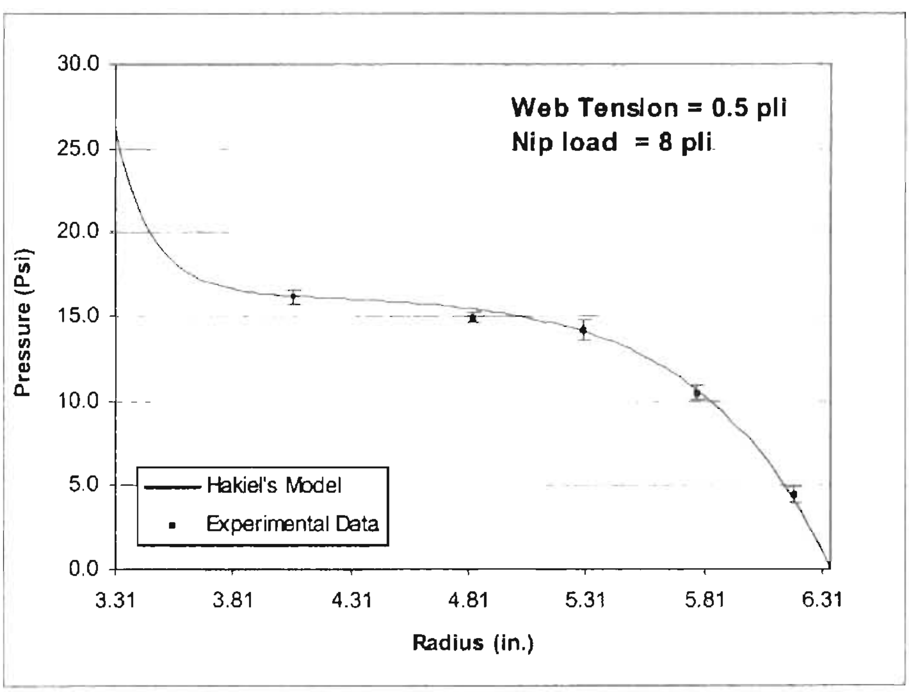

Figure A.2 Radial pressure profile at web tension = 0.5 pli and nip load = 8 pli

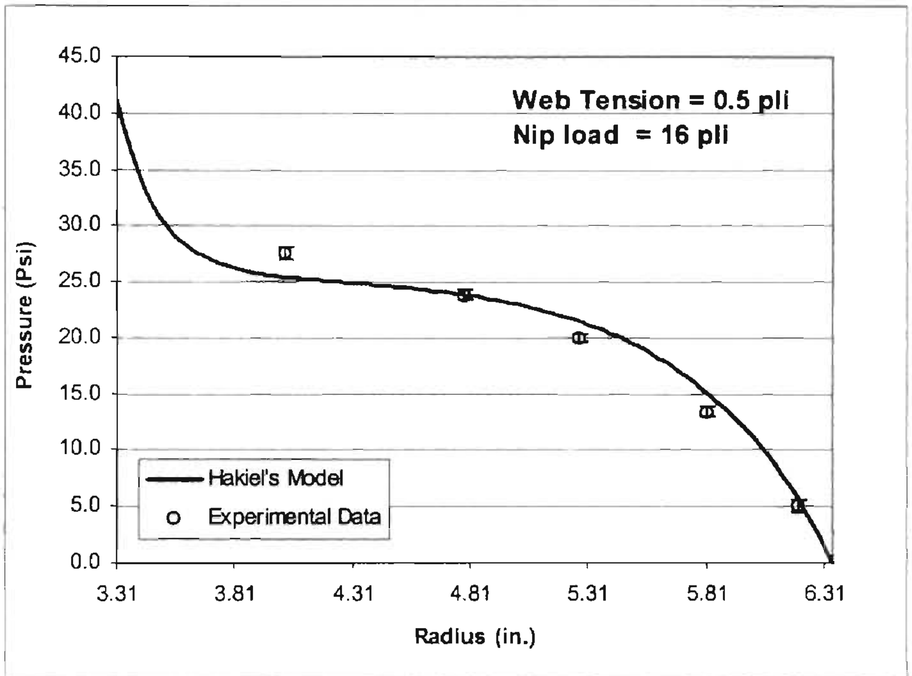

Figure A.3 Radial pressure profile at web tension = 0.5 pli and nip load = 16 pli

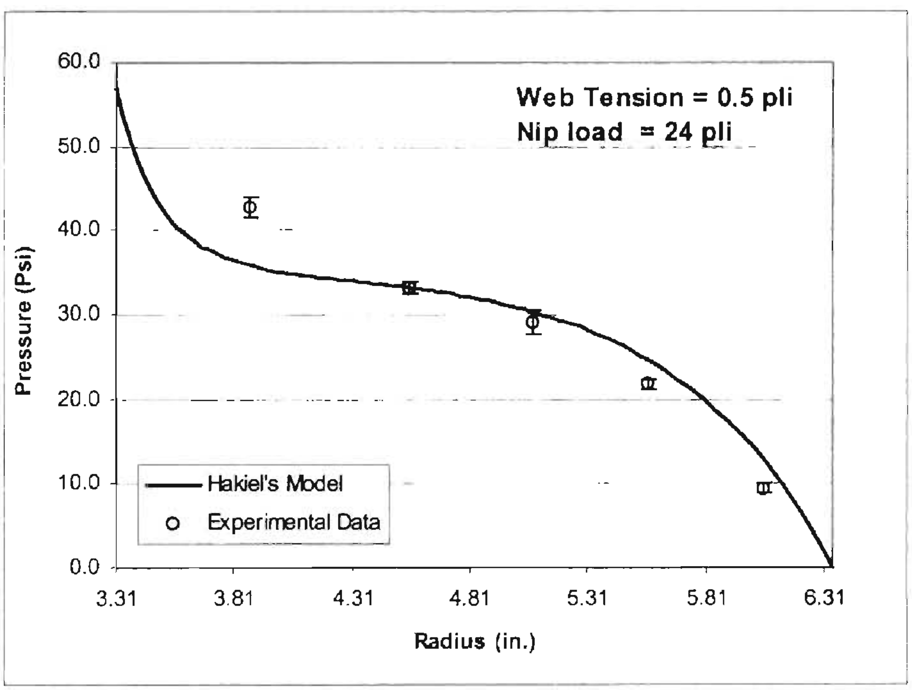

Figure A.4 Radial pressure profile at web tension = 0.5 pli and nip load = 24 pli

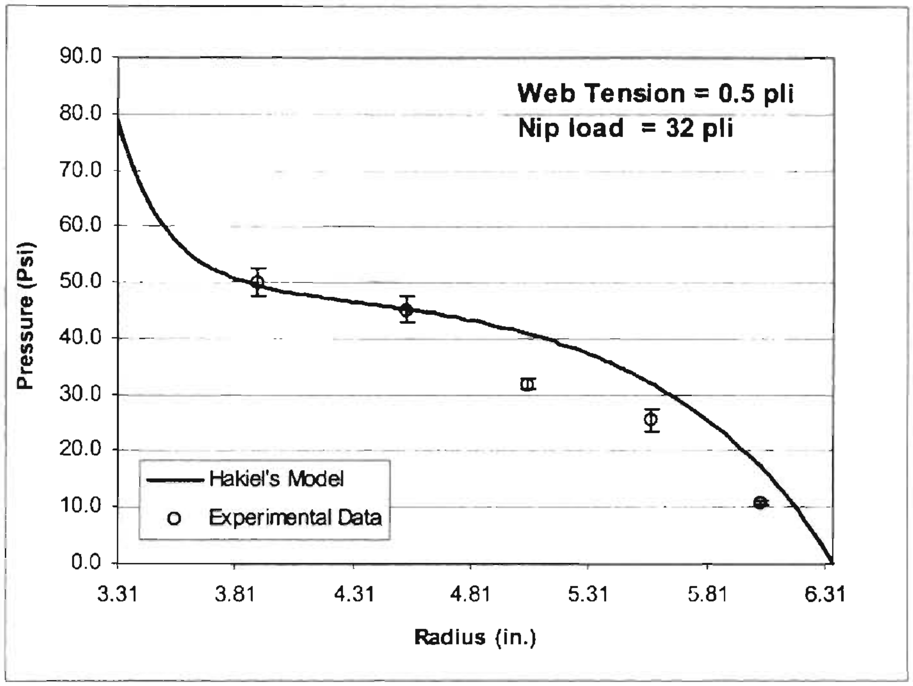

Figure A.5 Radial pressure profile at web tension = 0.5 pli and nip load = 32 pli

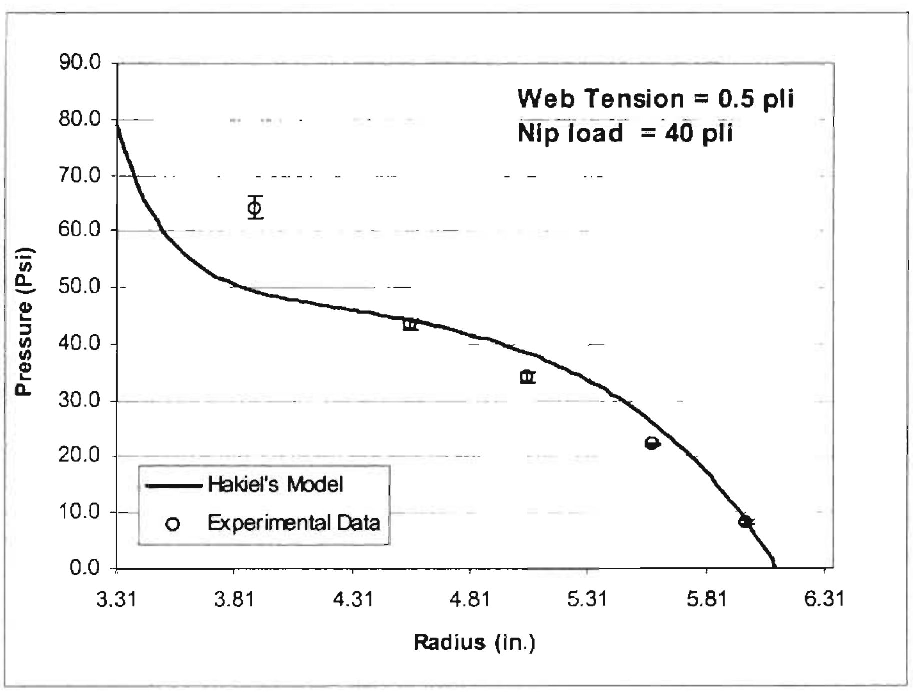

Figure A.6 Radial pressure profile at web tension = 0.5 pli and nip load = 40 pli

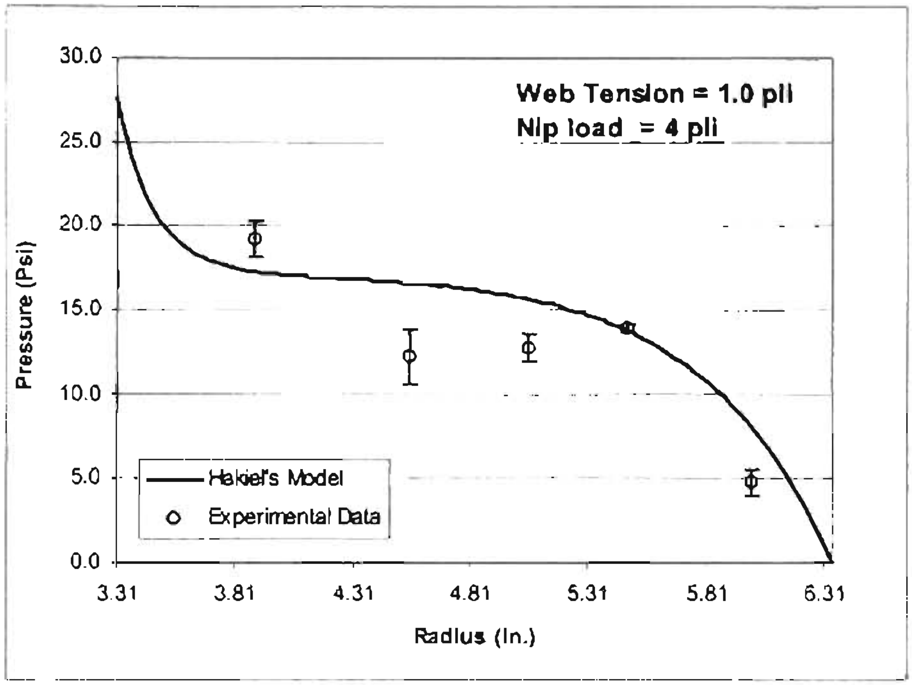

Figure A.7 Radial pressure profile at web tension = 1.0 pli and nip load = 4 pli

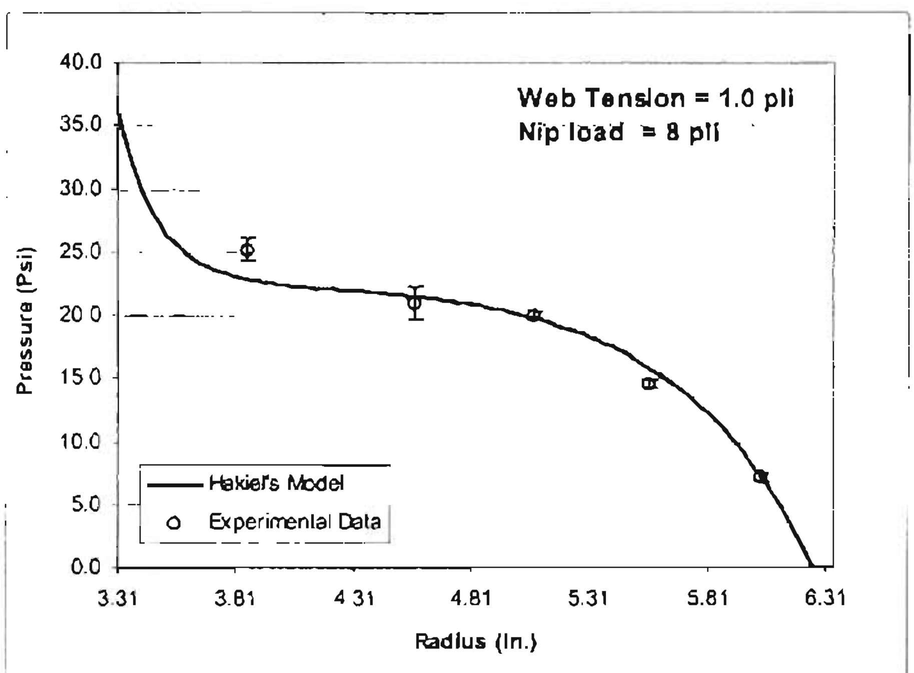

Figure A.8 Radial pressure profile at web tension = 1.0 pli and web tension = 8 pli

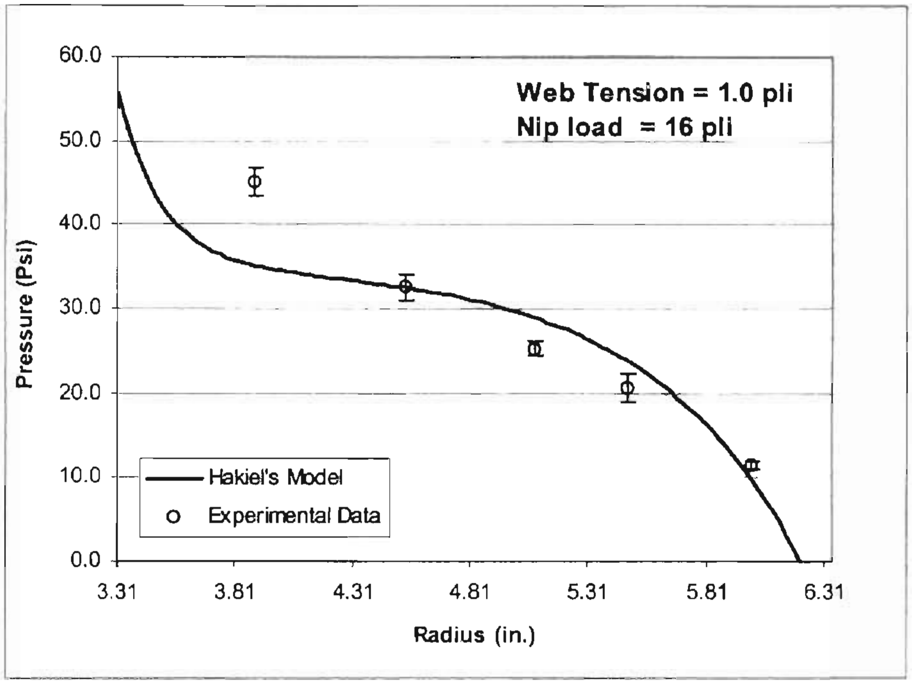

Figure A.9. Radial pressure profile at web tension = 1.0 pli and nip load = 16 pli

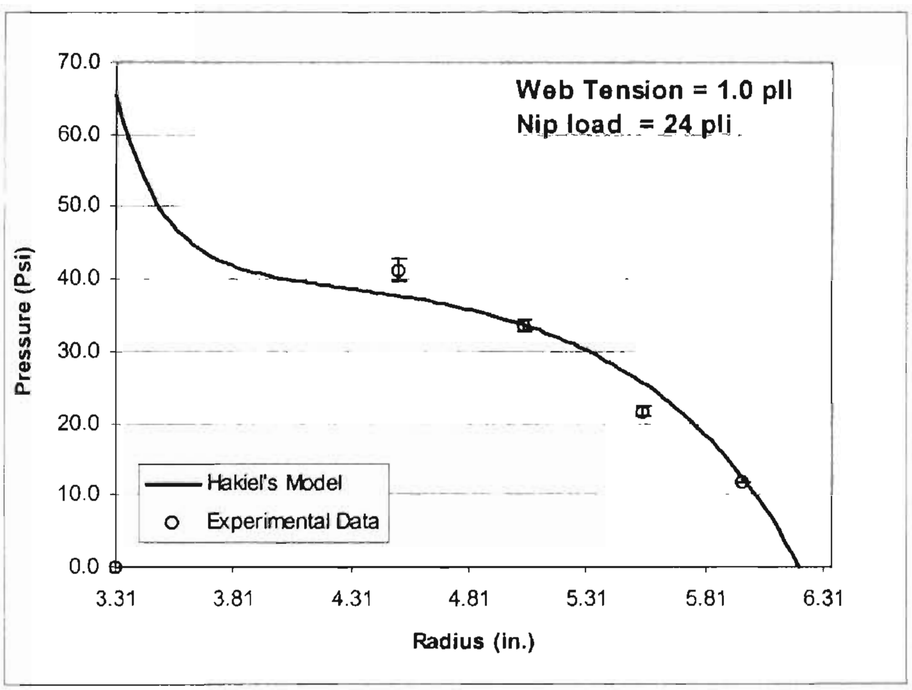

Figure A.10 Radial pressure profile at web tension = 1.0 pli and nip load = 24 pli

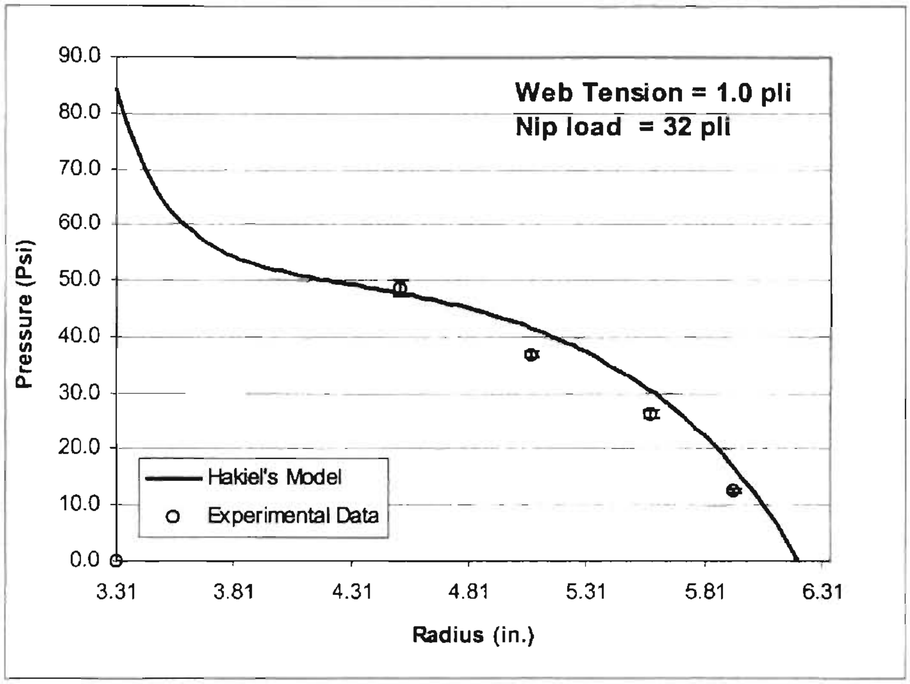

Figure A.11 Radial pressure profile at web tension = 1.0 pli and nip load = 32 pli

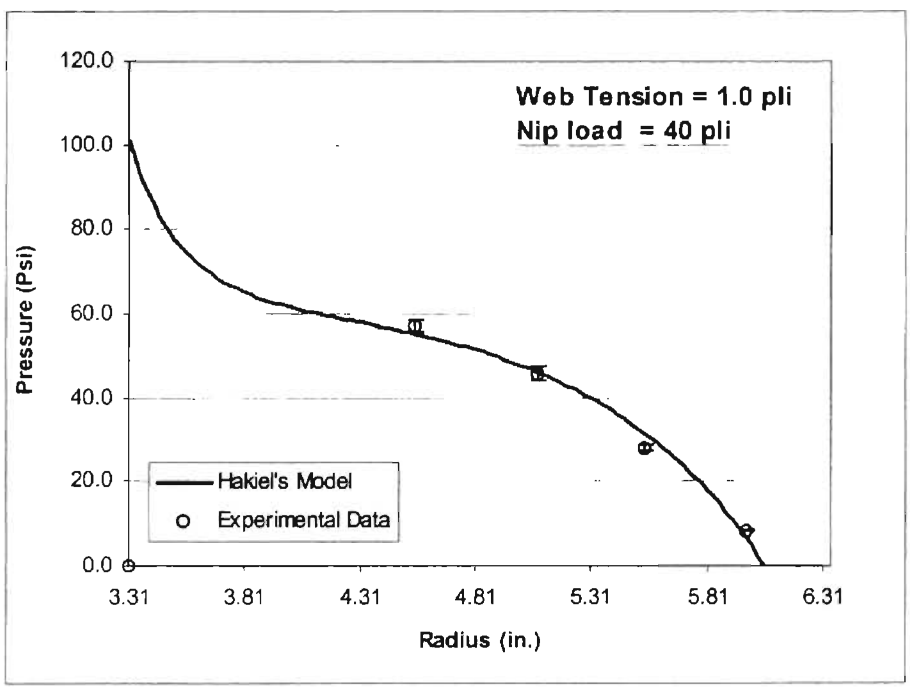

Figure A.12 Radial pressure profile at web tension = 1.0 pli and nip load = 40 pli

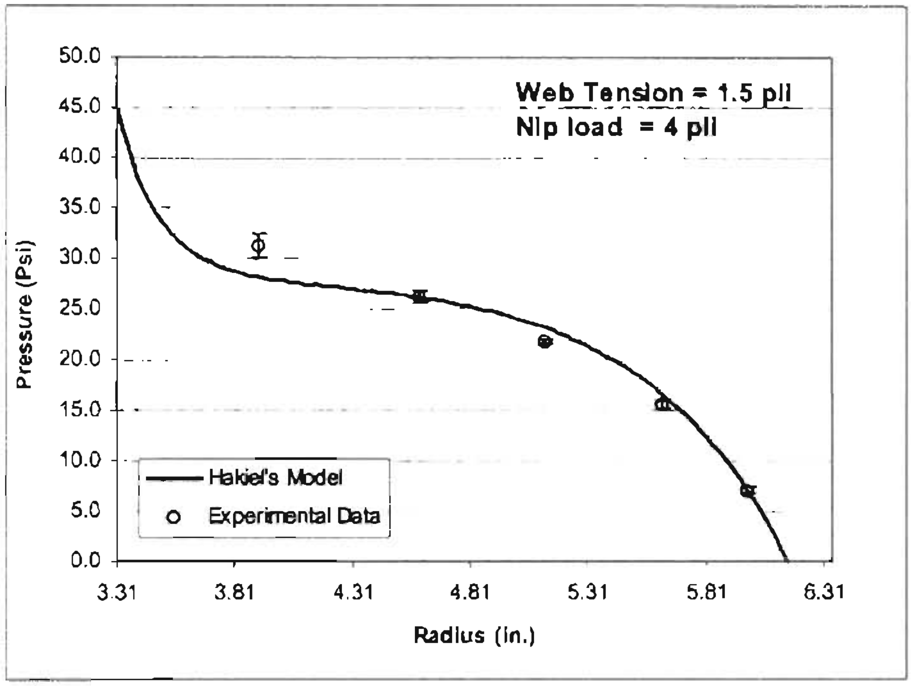

Figure A.13 Radial pressure profile at web tension = 1.5 pli and nip load = 4 pli

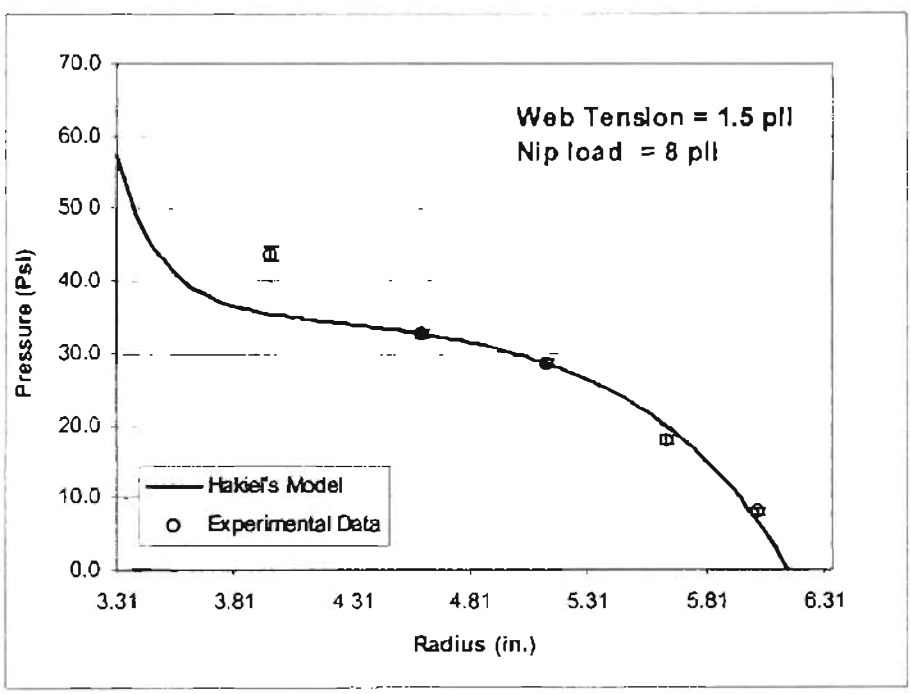

Figure A.14 Radial pressure profile at web tension = 1.5 pli and nip load = 8 pli

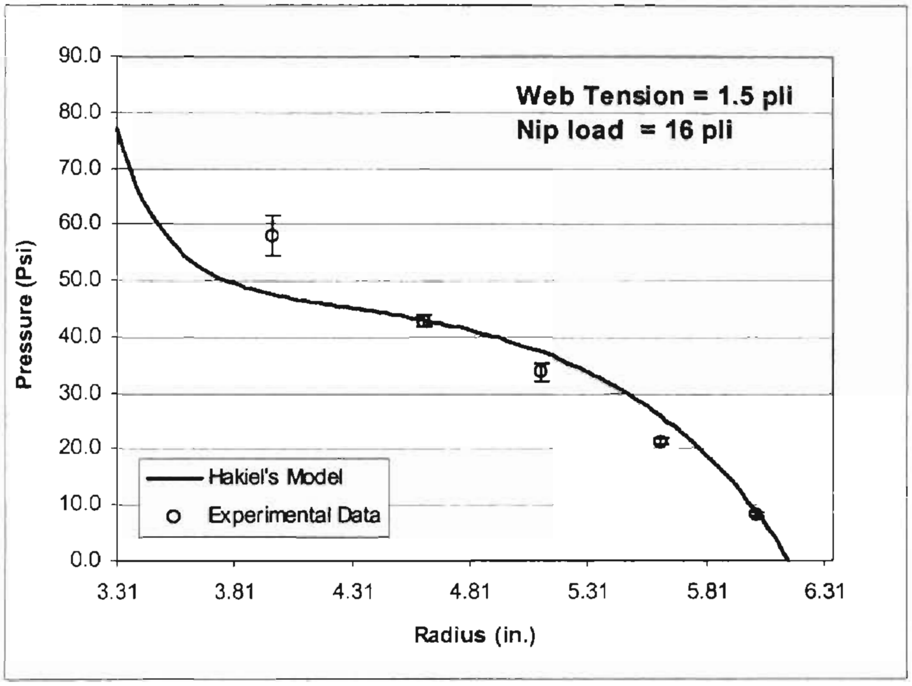

Figure A.15 Radial pressure profile at web tension = 1.5 pli and nip load = 16 pli

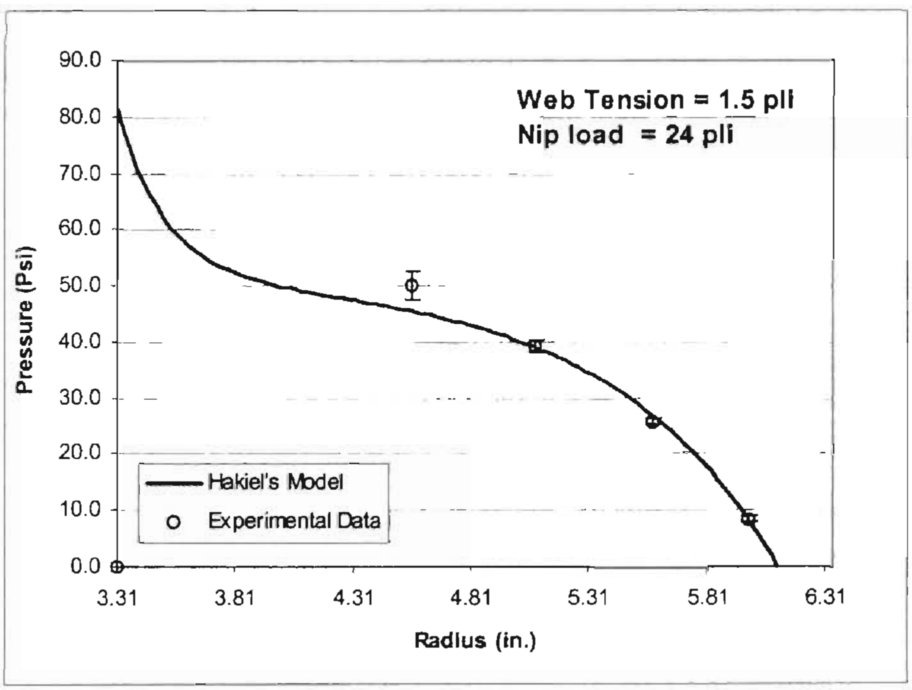

Figure A.16 Radial pressure profile at web tension = 1.5 pli and nip load = 24 pli

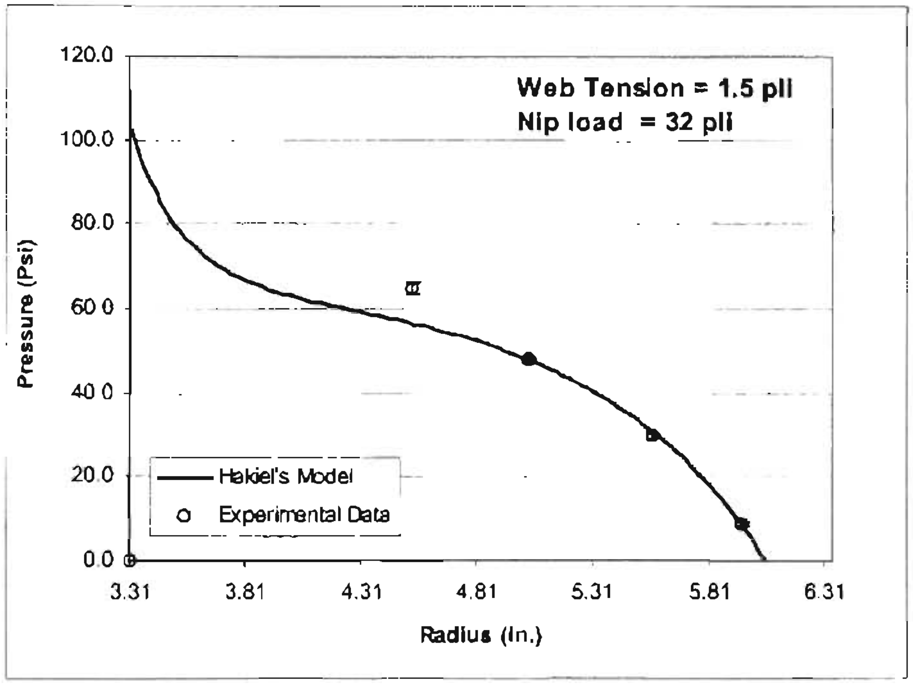

Figure A.17 Radial pressure profile at web tension = 1.5 pli and nip load = 32 pli

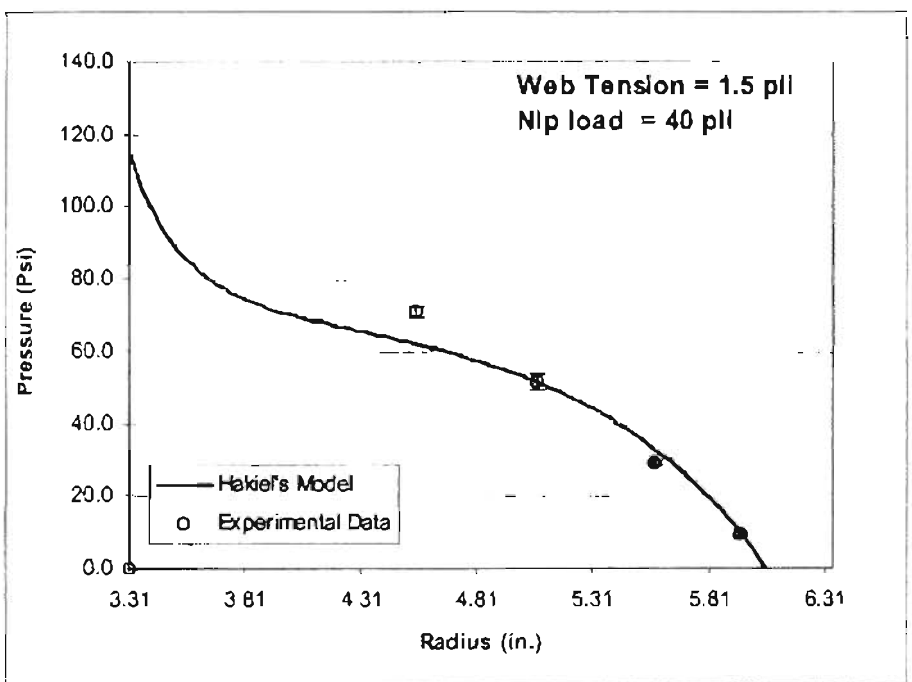

Figure A.18 Radial pressure profile at web tension = 1.5 pli and nip load = 40 pli

APPENDIX B

1. RADIAL PRESSURE VALUES FOR DIFFERENT WEB TENSION AND NIP LOAD VALUES

2. IN-PLANE MODULUS TEST DATA

3. RADIAL MODULUS TEST DATA

4. PHOTOGRAPHS OF WINDING MACHINE AT WHRC

Table B.1 Radial pressure values for different web tension and nip load values

Column 1. Confidence values *Column 2: Average Pile Height (in)* *Column 3: Average pressure (psi)*

Web tension =0.5 pli			Web tension = 1.0 pli			Web tension = 1.5 pli		
Nip load = 4 pli			Nip load = 4 pli			Nip load = 4 pli		
0.2999	0.7553	9.1316	1.0932	0.5803	19.1940	1.2379	0.6033	31.2536
0.1748	1.5017	8.2303	1.5896	1.2400	12.1876	0.5852	1.2900	26.1416
0.2903	2.0833	7.1434	0.8469	1.7497	12.7349	0.2361	1.8167	21.7695
0.2111	2.4250	6.4349	0.2349	2.1733	13.9355	0.4105	2.3167	15.5169
0.2763	2.9000	2.8764	0.7723	2.6967	4.7651	0.3305	2.6767	7.0928
Nip load = 8 pli			Nip load = 8 pli			Nip load = 8 pli		
0.4121	0.7527	16.1535	0.8706	0.5467	25.1582	1.0067	0.6500	43.7756
0.3229	1.5183	14.9126	1.2612	1.2573	20.9837	0.5230	1.2933	32.7373
0.6105	1.9923	14.1206	0.3106	1.7667	19.9423	0.3890	1.8233	28.5989
0.4381	2.4733	10.4732	0.3020	2.2590	14.5508	0.5526	2.3300	17.8438
0.4505	2.8840	4.4411	0.3429	2.7287	7.2248	0.3459	2.7167	8.0287
Nip load = 16 pli			Nip load = 16 pli			Nip load = 16 pli		
0.5216	0.7123	27.4805	1.6840	0.5867	45.1463	3.5434	0.6633	58.0227
0.4183	1.4773	23.8252	1.4782	1.2300	32.5337	1.0135	1.3067	42.9040
0.3474	1.9667	19.9187	0.8165	1.7733	25.2903	1.6205	1.8033	33.7812
0.4821	2.5033	13.3583	1.6278	2.1700	20.5972	0.5495	2.3067	21.3515
0.5476	2.8923	5.0261	0.4574	2.6900	11.5144	0.4660	2.7133	8.2985
Nip load = 24 pli			Nip load = 24 pli			Nip load = 24 pli		
1.1787	0.5623	42.7490						
0.7411	1.2413	33.1823	1.4993	1.2033	41.2297	2.5312	1.2533	49.9337
1.4455	1.7680	29.0133	0.7263	1.7343	33.6002	1.0443	1.7733	39.1228
0.5972	2.2523	21.8053	0.8044	2.2383	21.6846	0.4086	2.2700	25.7284
0.5435	2.7450	9.4356	0.1100	2.6557	11.7427	0.5735	2.6767	8.3870
Nip load = 32 pli			Nip load = 32 pli			Nip load = 32 pli		
3.2593	0.6233	47.1951						
0.4278	1.2400	35.5921	1.4104	1.2067	48.4918	1.6075	1.2233	64.7436
0.2900	1.7933	22.9922	0.6424	1.7633	36.8943	0.9018	1.7233	47.7636
0.4274	2.2500	16.8246	0.6525	2.2733	26.2279	0.6332	2.2600	29.6825
0.3125	2.5567	6.5201	0.2756	2.6233	12.6878	0.4460	2.6433	8.6715
Nip load = 40 pli			Nip load = 40 pli			Nip load = 40 pli		
1.9212	0.5867	64.2449						
0.9061	1.2467	43.4042	1.5237	1.2400	57.2624	1.3057	1.2400	70.8806
0.8125	1.7400	34.0628	1.6118	1.7733	45.7010	2.4102	1.7633	51.5195
0.2388	2.2700	22.2070	0.7075	2.2333	28.0157	0.4515	2.2667	28.9642
0.3715	2.6633	8.1237	0.3143	2.6667	8.2468	0.4670	2.6333	9.5834

Table B.2 In-plane modulus test Data

Average Strain (in/in)	Average Tangential Stress(psi)
0.00	0.00
1.25	55.56
2.00	111.11
2.74	166.67
3.44	222.22
4.30	277.78
5.18	333.33
6.00	388.89
6.94	444.44
7.97	500.00
9.27	555.56
11.81	694.44
14.34	833.33

Table B.3 Radial Modulus Test Data

Strain	Pressure (psi)	Radial Modulus	Strain	Pressure (psi)	Radial Modulus
0.01884	0.78605	49.18919488	0.05224	6.5109	353.3564786
0.0195	0.86887	54.24700139	0.05281	6.66619	357.0652561
0.0203	0.87922	57.59763327	0.0536	6.9457	370.1710492
0.02086	0.89993	59.60828743	0.05422	7.24592	379.2728335
0.02166	0.94134	59.65760252	0.05479	7.42191	390.43195
0.02222	1.00345	62.28535882	0.05549	7.74283	400.2498602
0.02282	1.06557	64.74962517	0.0562	7.97058	412.9503774
0.02364	1.08627	69.52513508	0.05681	8.26045	419.6952561
0.02421	1.11733	69.49500228	0.05744	8.51926	425.944508
0 02494	1 15874	70.24643747	0.05826	8.82983	431.3811889
0 02552	1.23121	73.63241733	0.05877	9.13005	444.8109873
0 02617	1.29332	77.78948303	0.05946	9.43027	457.9664434
0.02697	1.33473	90.00029208	0.0602	9.73048	468.2800987
0.02748	1.34508	97.69790786	0.06082	10.04105	480.1383973
0 02829	1.4279	99.30525944	0.06159	10.32057	489.3810793
0 02895	1.53142	100.1644398	0.06218	10.75537	498.1303371
0.02953	1.57283	106.1369934	0 0628	11.02453	507.6960567
0 03028	1 72812	111.2085965	0.06355	11.42827	517.8238937
0.03086	1.77988	118.4784269	0.06412	11.71814	526.1976568
0.03162	1.79023	122.6470816	0 06477	12.02871	533.9706385
0.03221	1.8627	126.5805267	0.06548	12 4635	532.351587
0.03282	1.97657	131.4212635	0.06614	12.75337	545.1364823
0.03363	2.04904	137.0413129	0.06687	13.16746	557.9921694
0.03424	2.19397	142.2308268	0.06748	13.54015	567.9078944
0.03482	2.27679	147.9070578	0 06812	13.88178	584.0090727
0.03558	2.39067	152.4881351	0.06894	14.32693	598.1236947
0.03616	2.46313	159.4476067	0.06943	14.67891	606 6787509
0.03698	2.61842	168.3927721	0.07009	15.11371	618.2973903
0.03764	2.64948	178.0536733	0 07089	15.53815	624.8808536
0.03818	2.74265	186.2125659	0 07146	15.9833	636.6964118
0 03895	2.93934	193.8013895	0.07209	16.3974	645.8105654
0 03947	3.08427	202.5752982	0.07291	16.79079	640.970443
0 04028	3.22921	208.9749992	0.07353	17.3084	645 0134333
0.04092	3.4259	219.0270587	0.07408	17.61897	657.7911167
0.04148	3.47766	217.0902528	0.07484	18.16765	667.2905114
0.04229	3.63295	220.0975659	0.07548	18.60245	680.87489
0.04293	3.79859	224.9754223	0.07629	19.01654	701.6693053
0.04349	3.91246	232.0360061	0.07686	19.46169	701.7569455
0.0443	4.14021	238.3875427	0.07745	19.95861	713.8451442
0.04493	4.22303	253 1106034	0.07808	20.43481	725.4087583
0.04546	4.44043	259 8113821	0 07887	20.97314	732.3169431
0.04626	4.62678	270.693284	0.07947	21.49076	746.452623
0.04683	4.76135	280.7536454	0.08026	21.94626	750.3348912
0.04748	4.9477	292.4417998	0.08084	22.43282	744.3729516
0.04828	5.20651	301 2772271	0.08144	22.92973	752.2109969
0.04883	5.32038	307.9434481	0.08221	23.41629	765.2696493
0.04946	5.5999	317 2441419	0.08283	23.98567	769.0711443
0.05026	5.81729	324.325577	0.08343	24.49294	788.1002625
0.05079	6.0347	334.8654134	0.08424	24.95879	793.7015261
0.05164	6.25209	341.7959697	0.08481	25.51782	796.1059744

Table B.3 Radial Modulus Test Data (Contd.)

Strain	Pressure (psi)	Radial Modulus	Strain	Pressure (psi)	Radial Modulus
0.08541	26.02508	811.122273	0.11881	59.03873	1135.106276
0.0862	26.58411	815.6330026	0.11932	59.73233	1149.355258
0.08683	27.2156	823.1359773	0.1201	60.42595	1159.13522
0.08747	27.71252	838.4700463	0.12077	61.3266	1161.748474
0.08817	28 19908	841.4602402	0 12136	62.07197	1180.12663
0.08878	28.83057	843.7003608	0.12214	62.79663	1176.838071
0.08939	29.32748	856.2499864	0.12274	63.68693	1180.047605
0.09018	29.94862	863.2476409	0 12337	64.44266	1197.321991
0.09079	30.52836	870.5857746	0.1241	65.17767	1192.438113
0.09137	31.06668	884.040547	0.12471	66.03692	1189.817345
0.09216	31.64641	889.7595054	0.12537	66.75123	1205.224191
0.09274	32.26755	892.6869018	0.12609	67.62083	1205.175546
0.09339	32.87834	904.0930194	0.12669	68.41796	1210.567532
0.09418	33.47878	909.4207555	0.12732	69.11156	1224.64888
0.09475	34.11027	916.9020722	0.12811	69.98116	1230.065717
0.09535	34.67965	925.5271478	0.12868	70.85076	1236.832647
0.09617	35.28008	929.0312076	0.12933	71.65824	1242.580269
0.09678	35.97369	933.0827727	0.13005	72.44502	1235.178024
0.09739	36.54307	942.5891459	0.13069	73.33533	1243.337797
0.0982	37.28844	944.6712645	0.13129	74.1221	1255.163059
0.09874	37.78535	950.5070965	0.13213	75.06417	1236.454794
0.09935	38.43755	961 368296	0.13272	75.87165	1246.205656
0.10015	39.11045	966.3333216	0.13346	76.62737	1260.208564
0.10073	39.71089	983.5861591	0.1341	77.55908	1269.566854
0.10136	40.35274	997.9721887	0.13462	78.35622	1277.094847
0.10219	41.09811	996.8250058	0.13545	79.10159	1294.938959
0.10272	41.65713	1005.383038	0.1361	80.13682	1292.974765
0.10336	42.39215	1020.381995	0.13673	80.99608	1302.065021
0.10414	43.23069	1029.948186	0.13729	81.78284	1292.813461
0.10475	43.83113	1038.481993	0.13815	82.77666	1287.53577
0.10551	44.43156	1045.181117	0.13868	83.53239	1302.772539
0.10618	45.25975	1034.918342	0.13943	84.39163	1291.015678
0.10671	45.83948	1038.747276	0.14011	85.35441	1284.058333
0.10733	46.54344	1045.902073	0.14072	86.09978	1298.445068
0.10814	47.36128	1054.748267	0.14143	86.96937	1313.744959
0.10872	47.94101	1066.434177	0.14207	87.93214	1306.883575
0.10947	48.60356	1061.308476	0.14264	88.65681	1324.950242
0.11014	49.48351	1063.853558	0.14343	89.56781	1335.924587
0.11068	50.03218	1063.728471	0.1441	90.65481	1331.480452
0.11135	50.72579	1076.838968	0.14467	91.41053	1339.64399
0.11212	51.60574	1090.070215	0.14547	92.25942	1342.170091
0.11273	52.24759	1097.654447	0.14605	93.25325	1346.974168
0.11336	52.92049	1097.210178	0.1466	94.06073	1352.235738
0 11415	53.70727	1111.563611	0.14744	94.90962	1356.44477
0.11474	54.46299	1110.427156	0 1481	96.00697	1355.766616
0 11532	55.14625	1115.000463	0.14864	96.75234	1376 005231
0 1161	55.96408	1129.500637	0.14941	97.71511	1374.516163
0 11682	56.81297	1127.902498	0.15006	98.62611	1374.238507
0 11735	57.47552	1135.001152	0.15062	99.54748	1393.753744
0.11815	58.18984	1138.257398	0.15146	100.44814	1401.547179

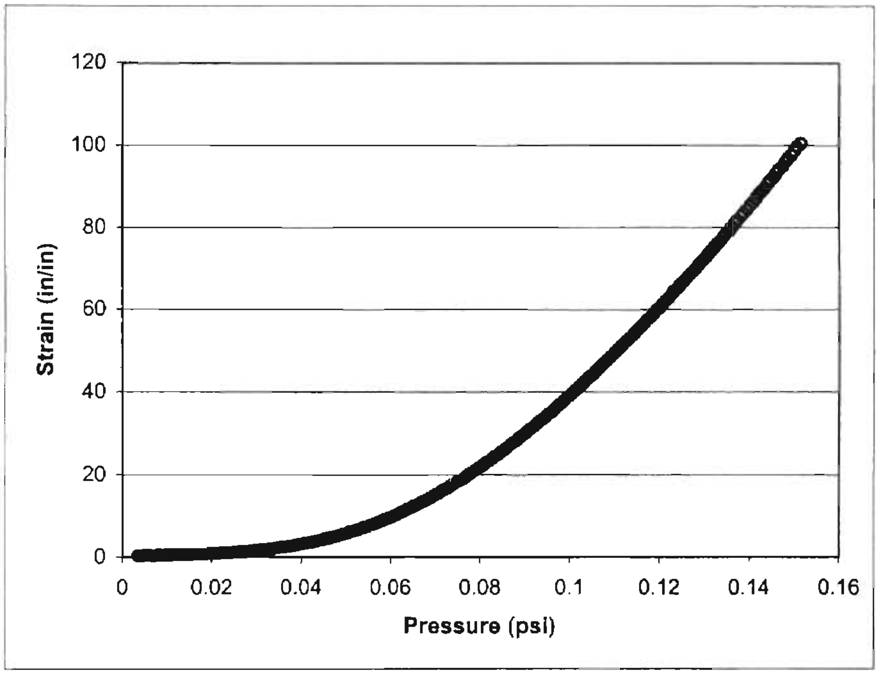

Figure B.1 Pressure Vs Strain Plot in Radial Modulus Test

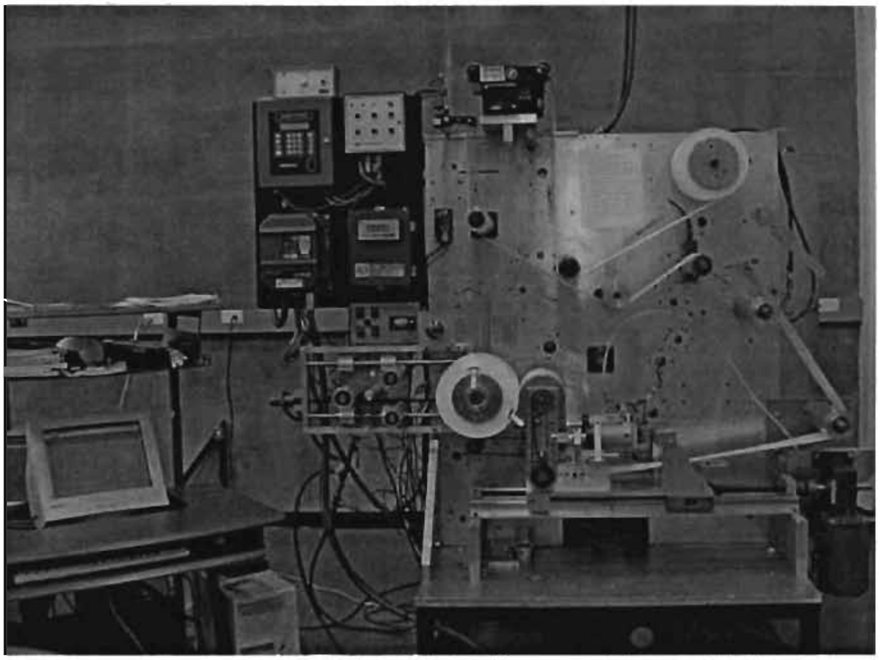

Figure B.2 WOTM Winding machine at WHRC

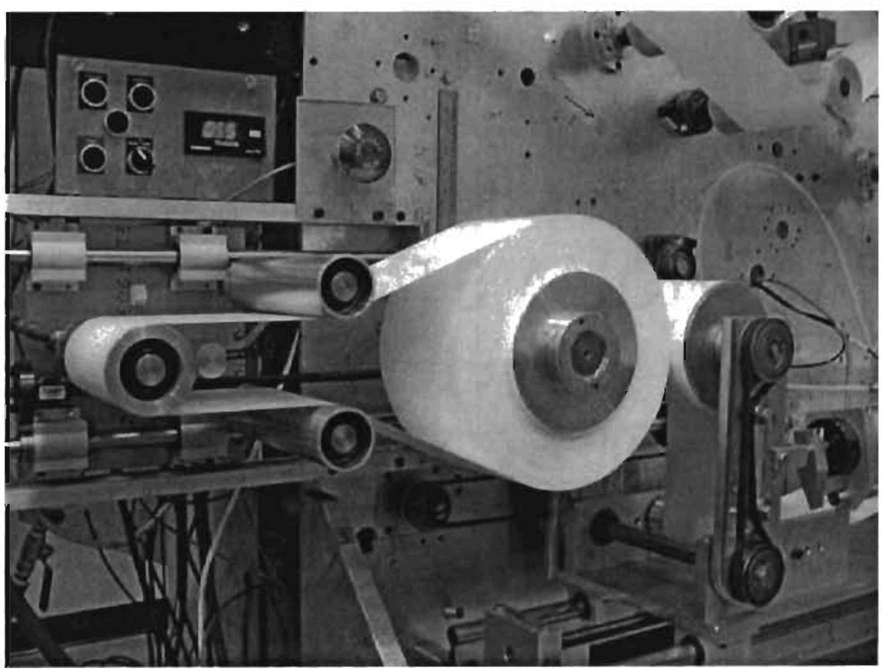

Figure B.3 Direct WOT Measurement

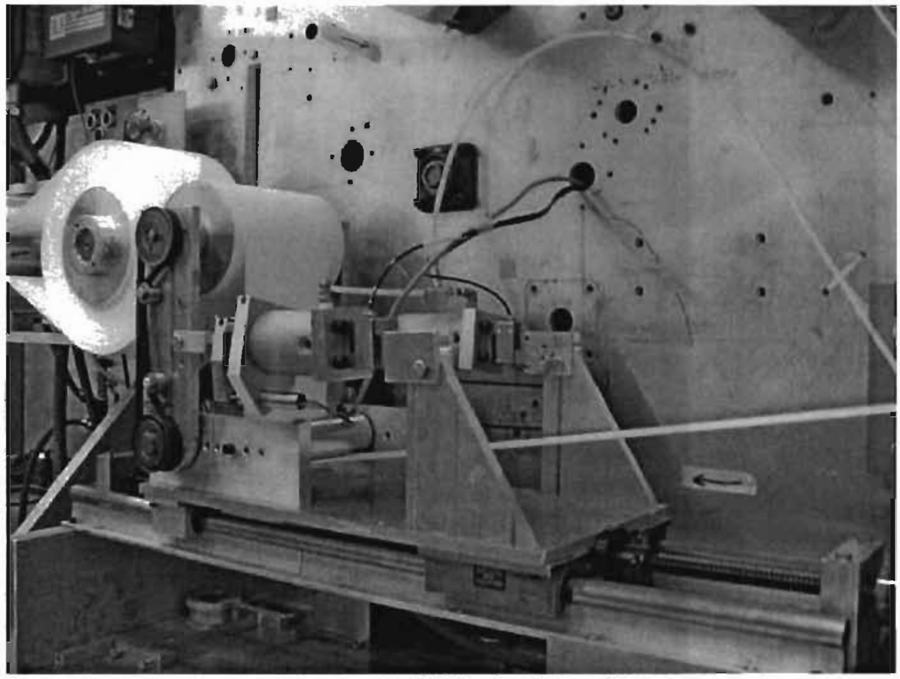

Figure B.4 Nip loading Setup

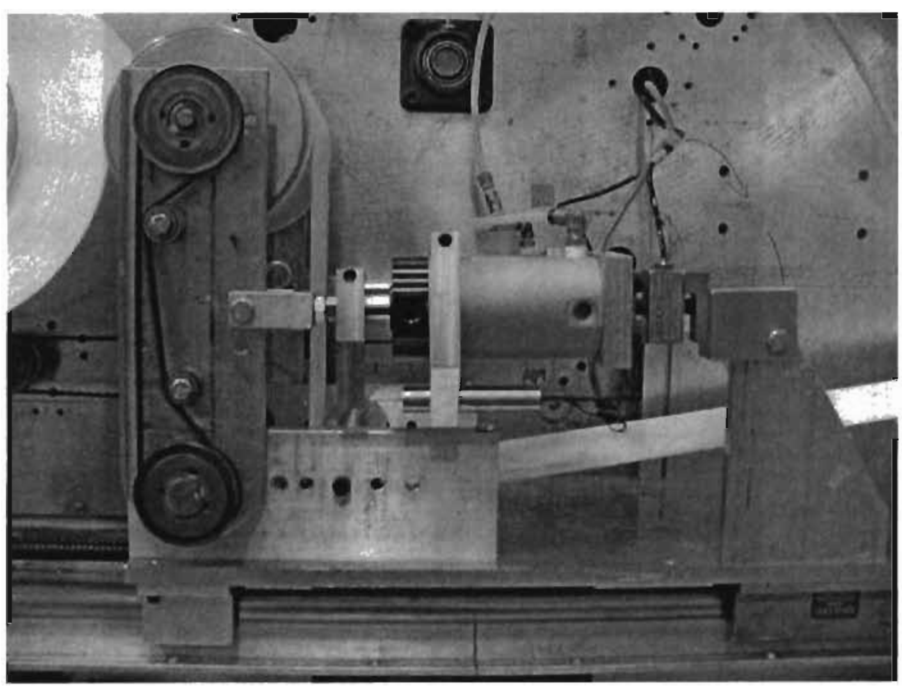

Figure B.5 Another view of the new setup

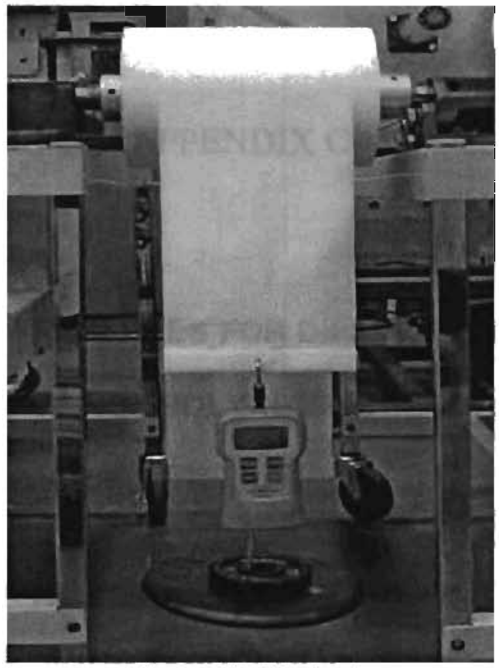

Figure B.6 Friction test

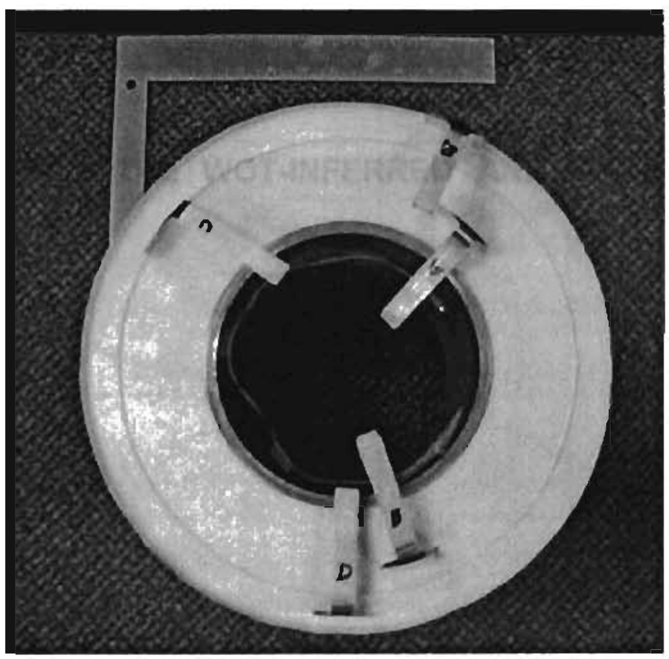

Figure B.7 Wound roll with pull-tabs

APPENDIX C

1. PLOTS OF RADIAL PRESSURES FOR DIFFERENT WEB LINE TENSIONS AND NIP LOADS USING POLYNOMIAL EQUATION FOR RADIAL MODULUS OF ELASTICITY

2. COMPARISON OF THE WOUND-ON TENSION VALUES OBTAINED USING PFEIFFER'S FORM AND POLYNOMIAL FORM FOR RADIAL MODULUS OF ELASTICITY

3. COMPARISON OF THE NIP-INDUCED TENSION VALUES

4. COMPARISON OF THE WOT-INFERRED AND CALCULATED USING EQUATION

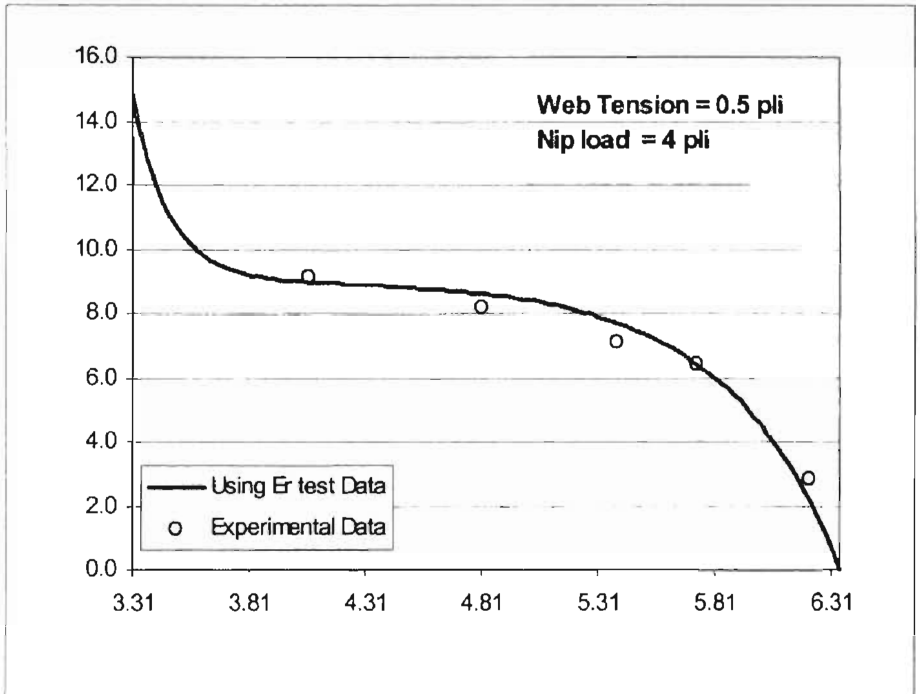

Figure C.1. Radial Pressure profile at Web tension = 0.5 pli and nip load = 4 pli

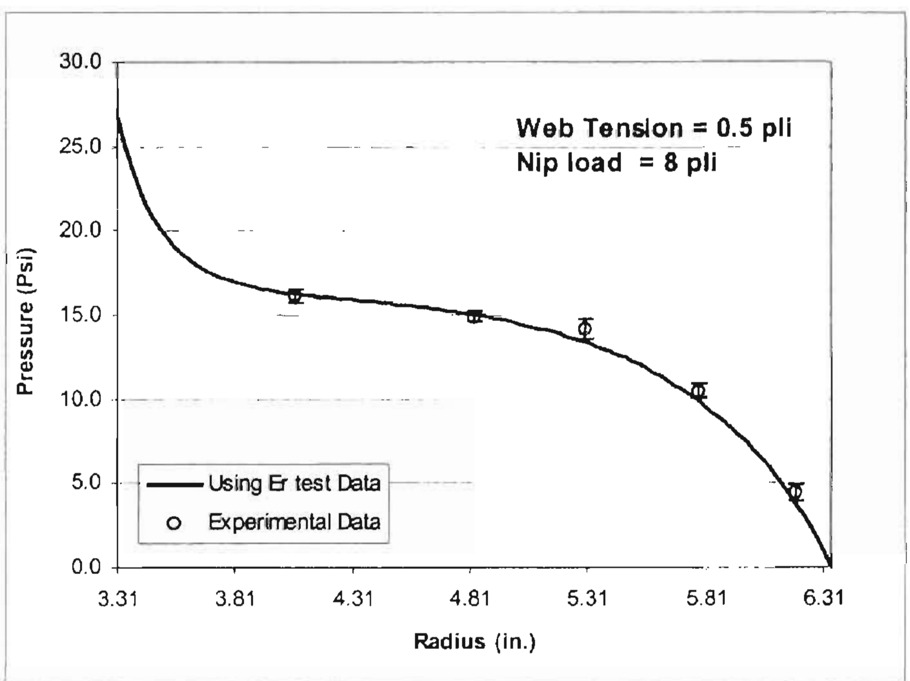

Figure C.2 Radial Pressure profile at Web tension = 0.5 pli and nip load = 8 pli

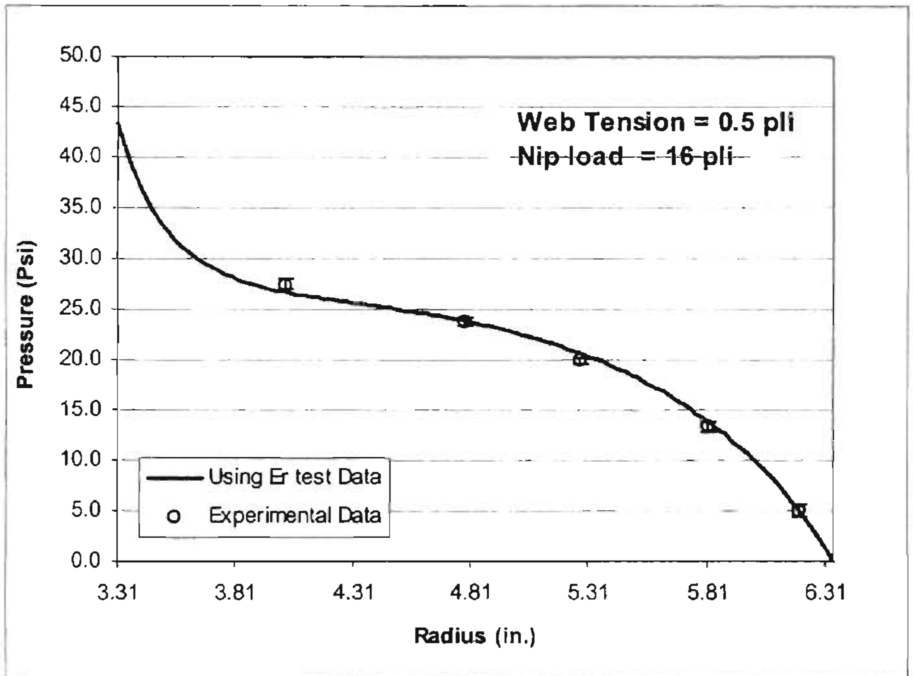

Figure C.3 Radial Pressure profile at Web tension = 0.5 pli and nip load = 16 pli

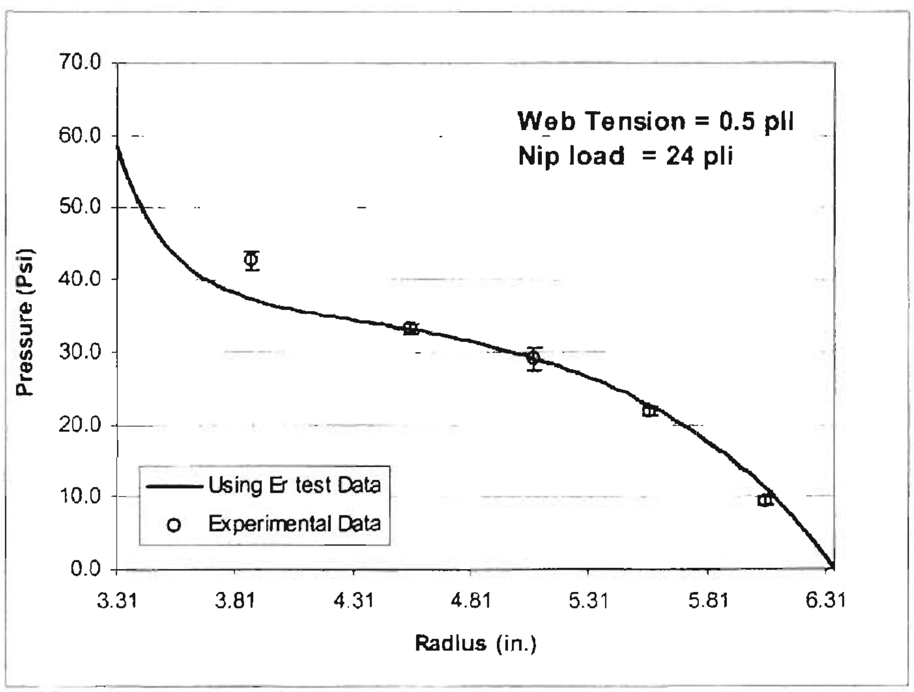

Figure C.4 Radial Pressure profile at Web tension = 0.5 pli and nip load = 24 pli

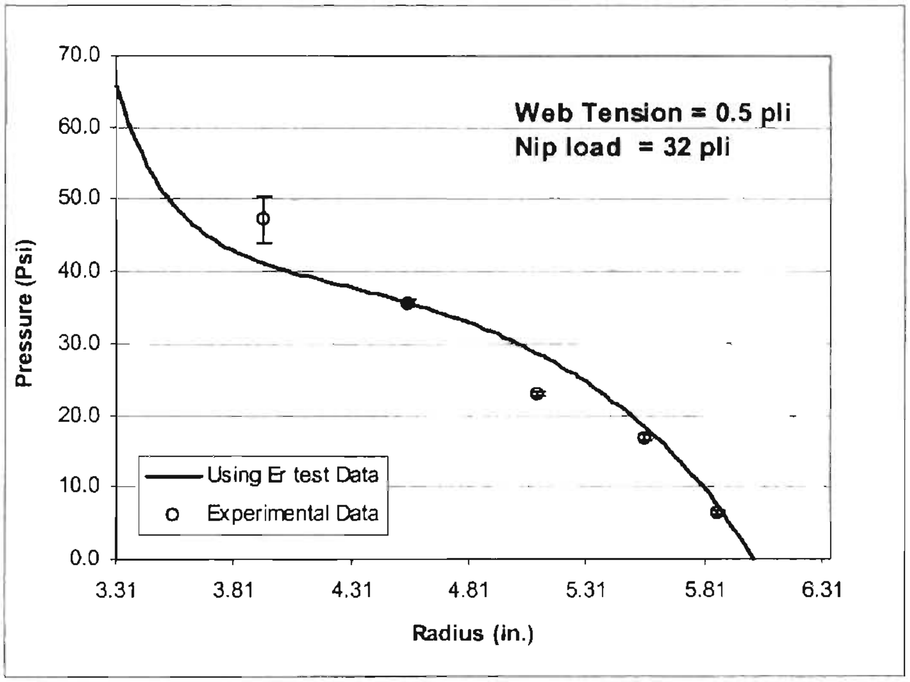

Figure C.5 Radial Pressure profile at Web tension = 0.5 pli and nip load = 32 pli

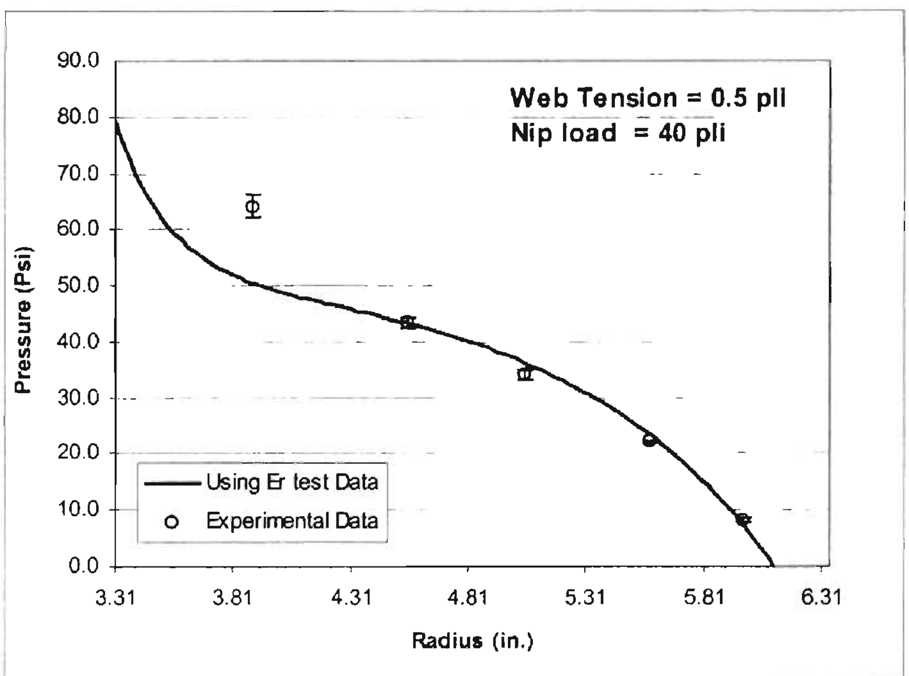

Figure C.6 Radial Pressure profile at Web tension = 0.5 pli and nip load = 40 pli

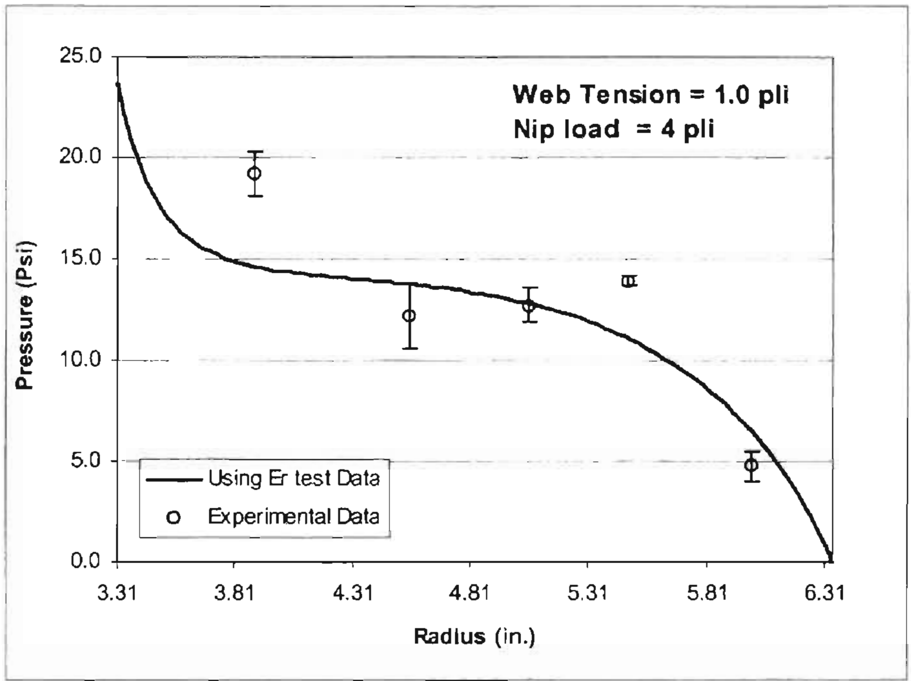

Figure C.7 Radial Pressure profile at Web tension = 1.0 pli and nip load = 4 pli

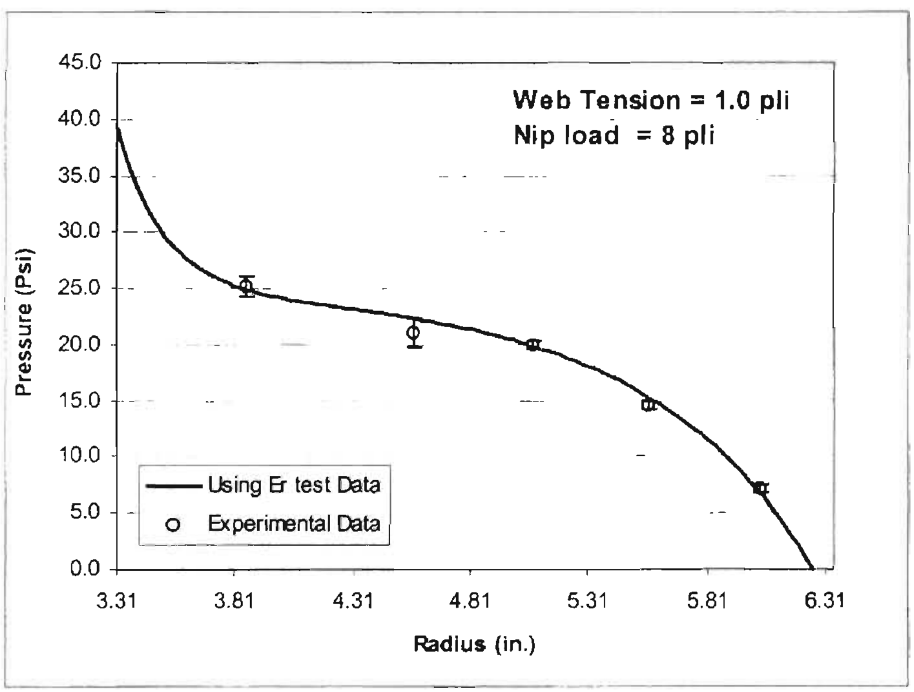

Figure C.8 Radial Pressure profile at Web tension = 1.0 pli and nip load = 8 pli

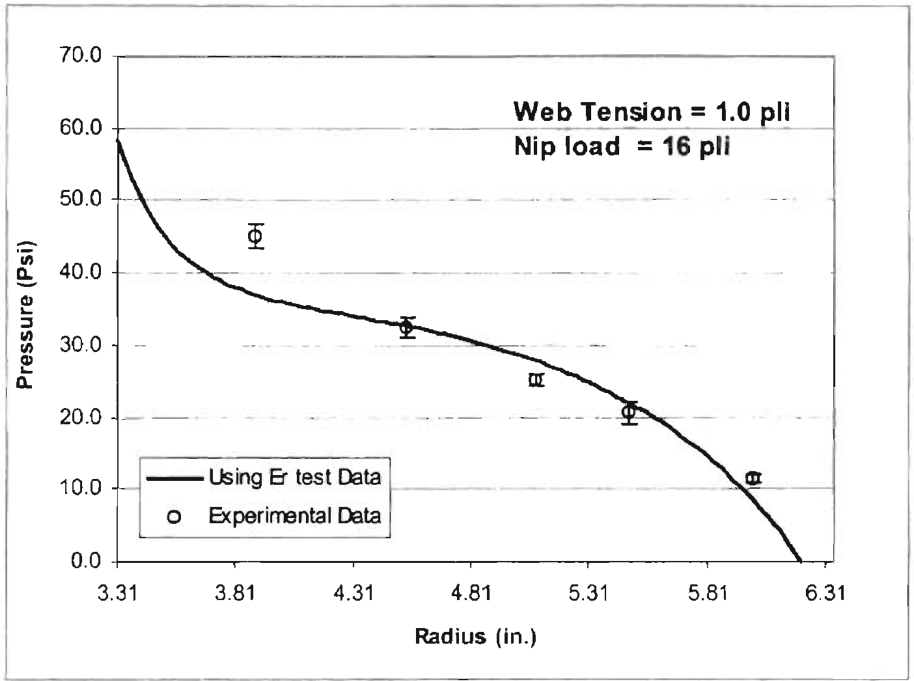

Figure C.9 Radial Pressure profile at Web tension = 1.0 pli and nip load = 16 pli

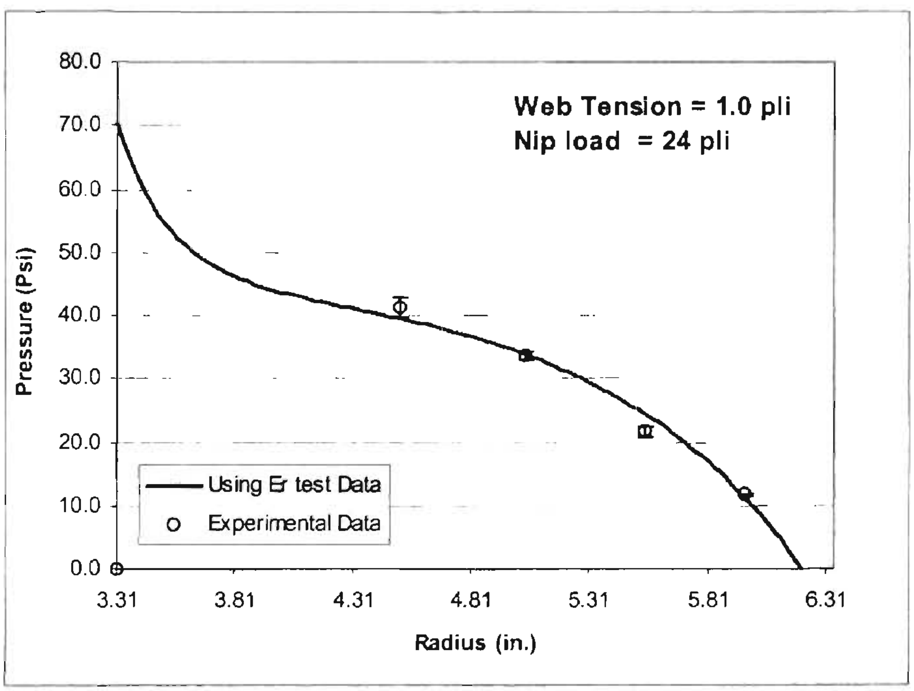

Figure C.10 Radial Pressure profile at Web tension = 1.0 pli and nip load = 24 pli

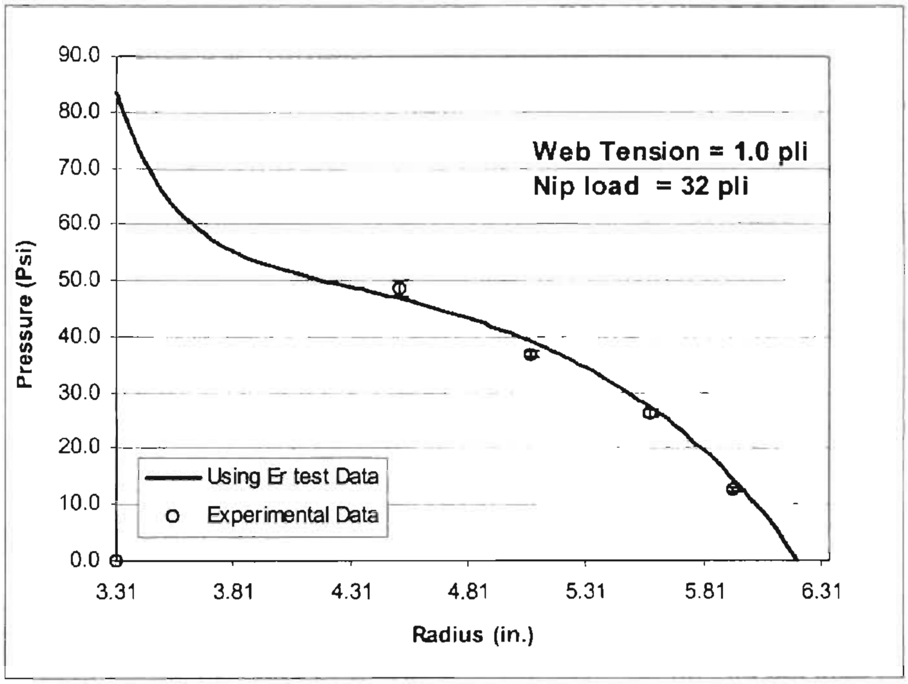

Figure C.11 Radial Pressure profile at Web tension = 1.0 pli and nip load = 32 pli

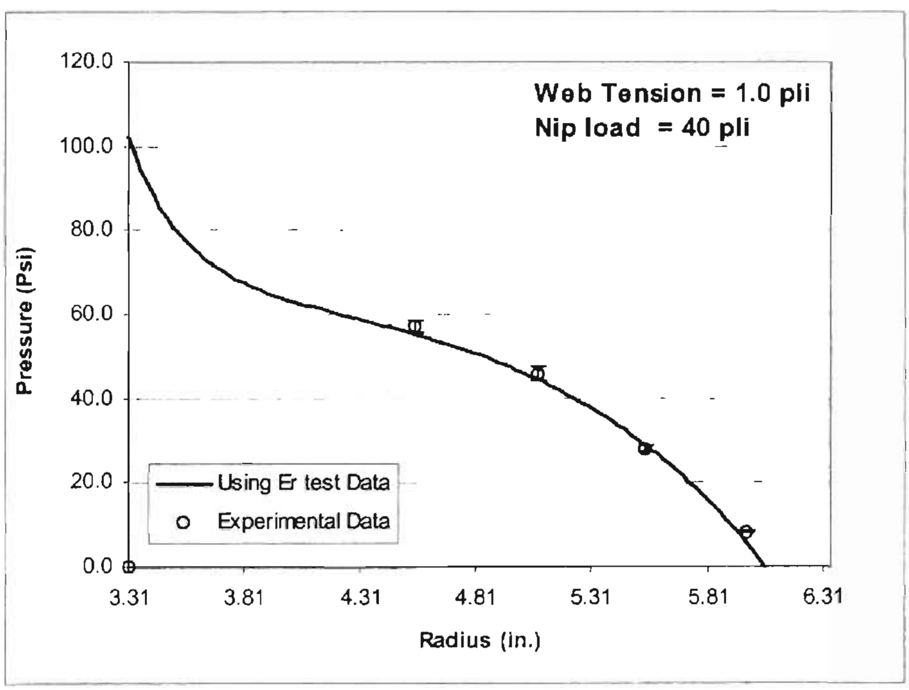

Figure C.12 Radial Pressure profile at Web tension = 1.0 pli and nip load = 40 pli

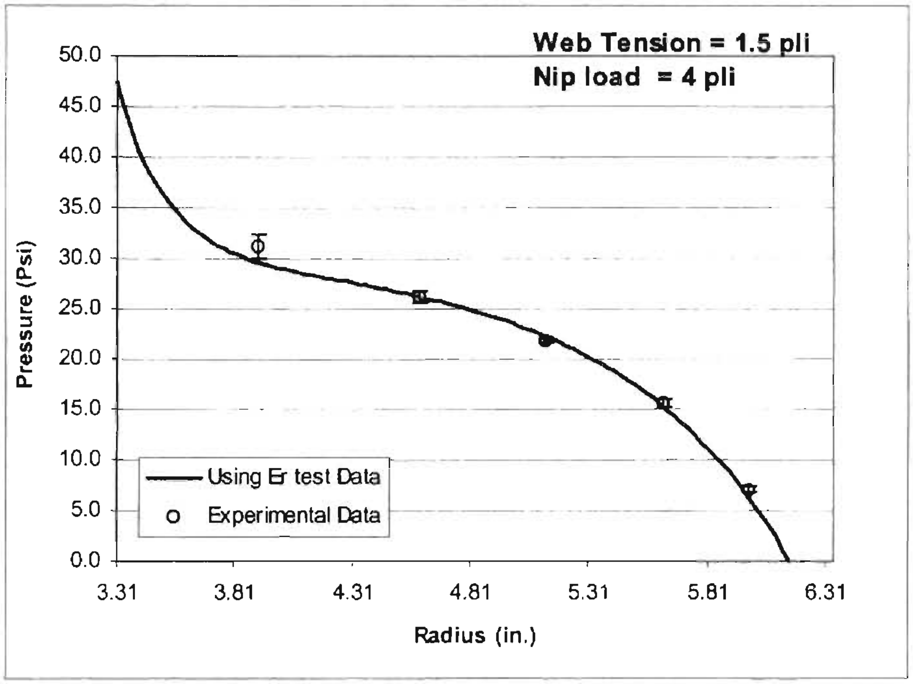

Figure C.13 Radial Pressure profile at Web tension = 1.5 pli and nip load = 4 pli

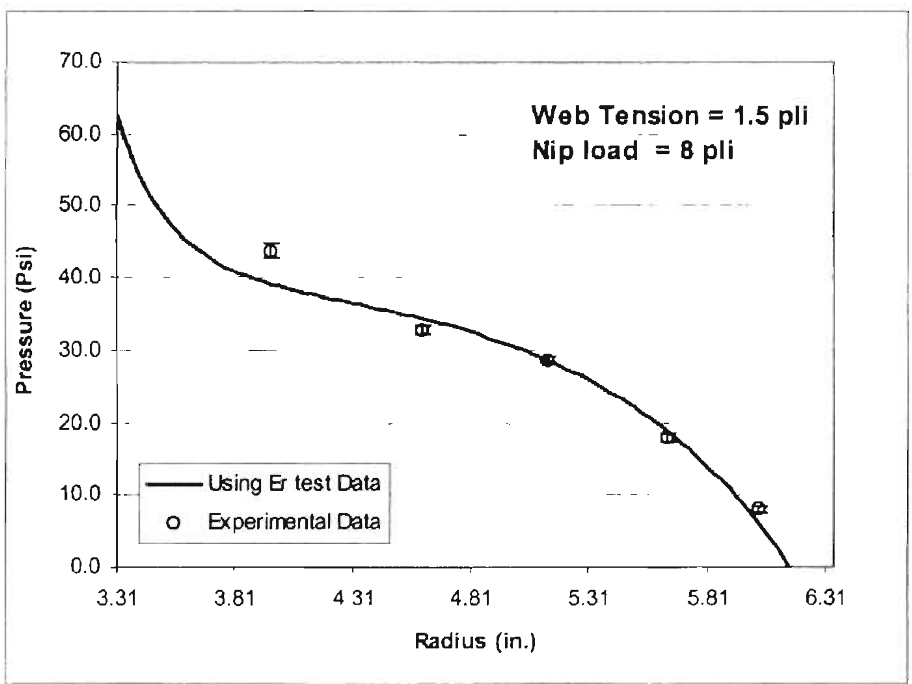

Figure C.14 Radial Pressure profile at Web tension = 1.5 pli and nip load = 8 pli

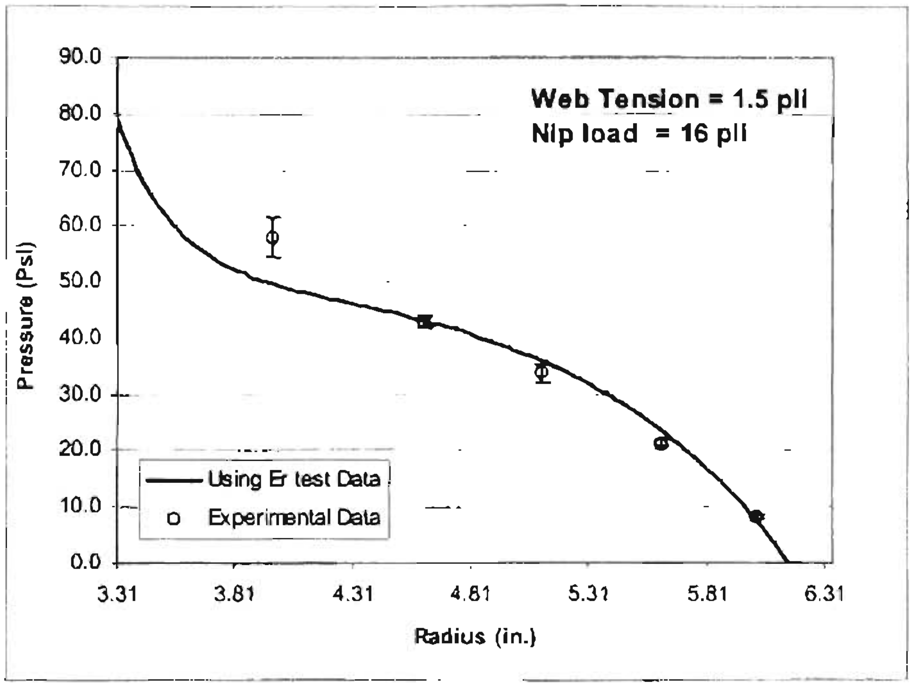

Figure C.15 Radial Pressure profile at Web tension = 1.5 pli and nip load = 16 pli

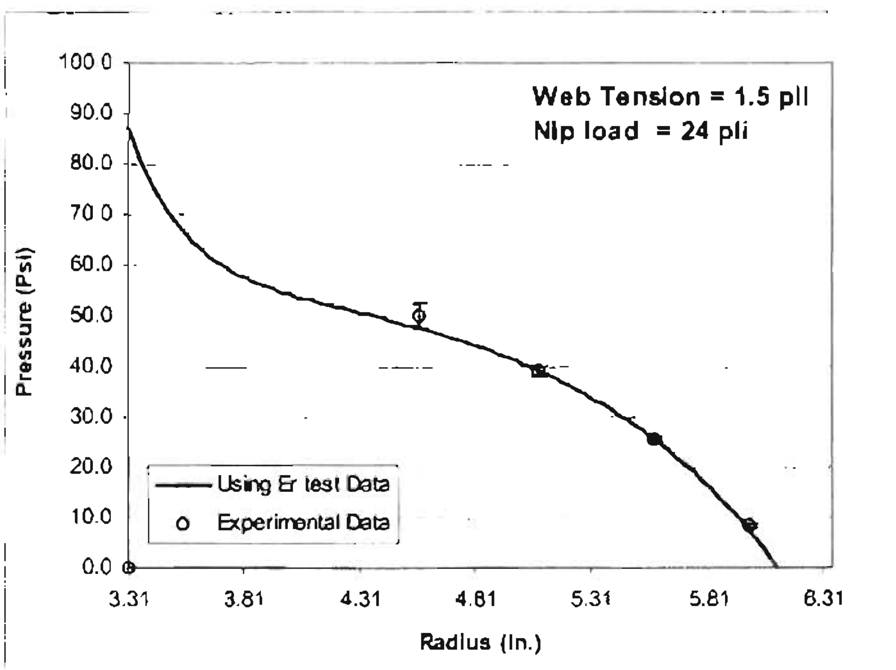

Figure C.16 Radial Pressure profile at Web tension = 1.5 pli and nip load = 24 pli

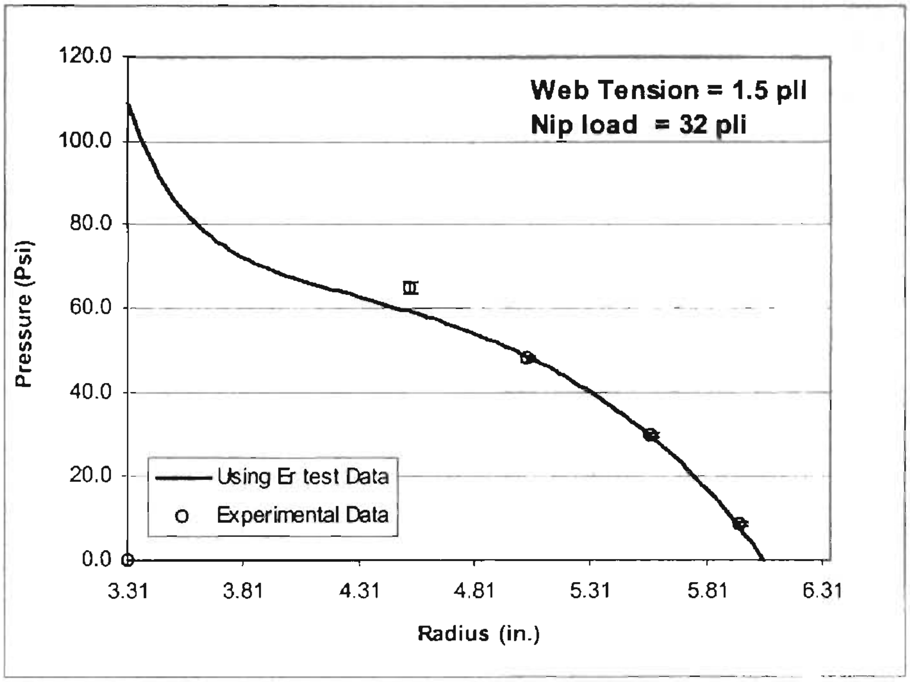

Figure C.17 Radial Pressure profile at Web tension = 1.5 pli and nip load = 32 pli

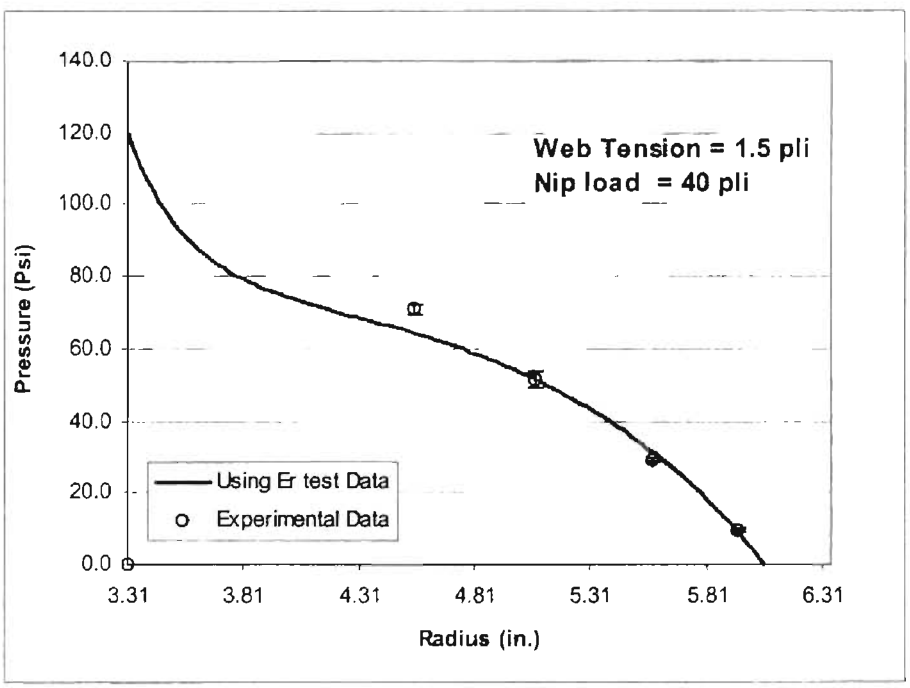

Figure C.18 Radial Pressure profile at Web tension = 1.5 pli and nip load = 40 pli

Table C.1 WOT values using Pfeiffer's and Polynomial form for Radial modulus

	WOT(Pfeiffer's form) pli			WOT(Polynomial form) pli		
Nip load (pli)	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli
4	0.69	1.206	1.776	0.762	1.02	1.59
8	1.158	1.5	2.124	1.104	1.41	1.926
16	1.656	2.088	2.622	1.5	1.83	2.28
24	1.956	2.334	2.73	1.83	2.088	2.52
32	2.34	2.79	3.216	2.004	2.37	2.868
40	2.67	3.168	3.456	2.28	2.766	3.126

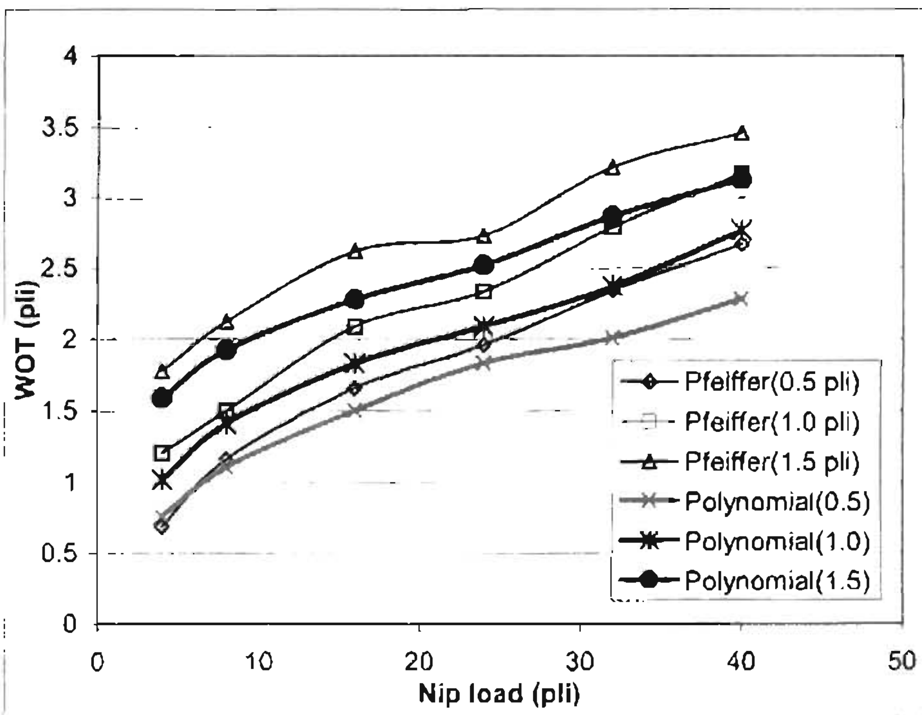

Figure C.19 Variation of WOT with nip load and web tension

Table C.2 NIT values using Pfeiffer's and polynomial form for Radial Modulus

	NIT(Pfeiffer's form) pli			NIT(polynomial form) pli		
Nip load (pli)	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli
4	0.19	0.206	0.276	0.262	0.02	0.09
8	0.658	0.5	0.624	0.604	0.41	0.426
16	1.156	1.088	1.122	1	0.83	0.78
24	1.456	1.334	1.23	1.33	1.088	1.02
32	1.84	1.79	1.716	1.504	1.37	1.368
40	2.17	2.168	1.956	1.78	1.766	1.626

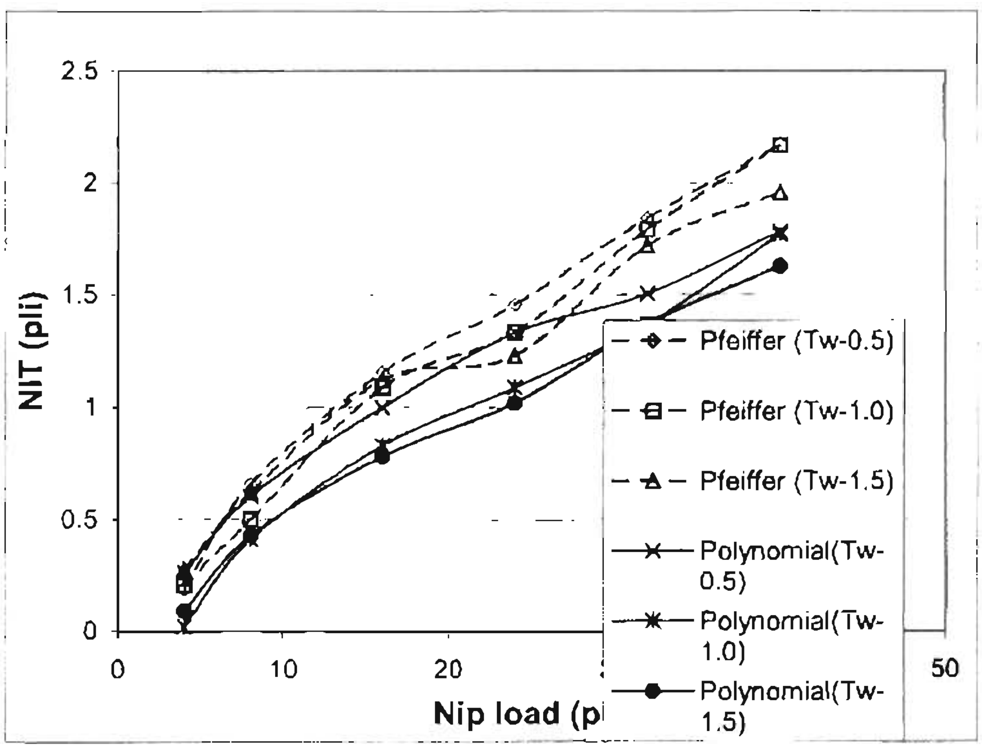

Figure C.20 Variation of NIT with nip load and web tension

Table C.3 Comparison of WOT values inferred and calculated from equation 4.2

	WOT – inferred pli			Analytical WOT - equation pli		
Nip load (pli)	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli	Tw=0.5 pli	Tw=1.0 pli	Tw=1.5 pli
4	0.762	1.02	1.59	0.754	1.254	1.754
8	1.104	1.41	1.926	1.008	1.508	2.008
16	1.5	1.83	2.28	1.516	2.016	2.516
24	1.83	2.088	2.52	2.024	2.524	3.024
32	2.004	2.37	2.868	2.532	3.032	3.532
40	2.28	2.766	3.126	3.04	3.54	4.04

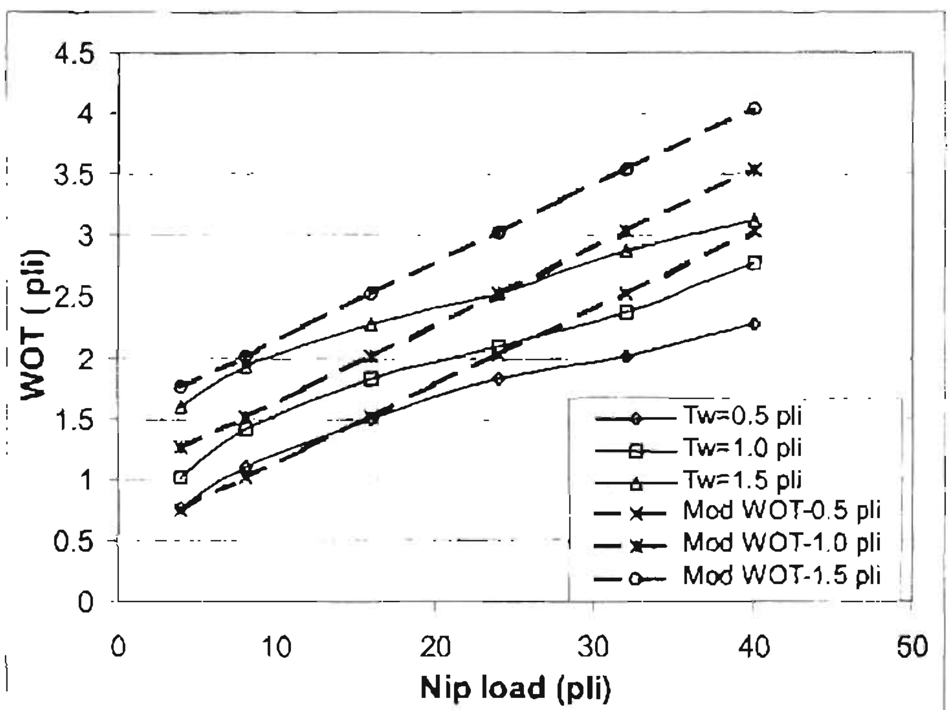

Figure C.21 Variation of WOT inferred and calculated using equation 4.2

VITA

Karthik Ayodhiramanujan

Candidate for the Degree of

Master of Science

Thesis: A STUDY OF THE WOUND-ON-TENSION MEASUREMENT METHOD IN CENTER WINDING CONDITION ON TYVEK® WEBS

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Chennai, Tamilnadu, India, On May 31, 1977, the son of Srinivasan Ayodhiramanujan and Raghavachari Ganapriya.

Education: Graduated from M.A. Matriculation Higher Secondary School, Karaikudi, India in May 1995; received Bachelor of Engineering in Mechanical Engineering from South Gujarat University, Gujarat, India in June 1999. Completed the requirements for the Master of Science degree with a major in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in August 2001.

Experience: Employed by the Department of Mechanical Engineering at Oklahoma State University, as a graduate teaching and research assistant, September 1999 to present. Employed by the College of Business Administration at Oklahoma State University, Stillwater as a graduate assistant, February 2001 to present. Employed by Kirloskar Oil Engines Ltd., India as a Graduate Engineer Trainee, August 1998 – June 1999.